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Utilization of lidar data and street view images in road environment monitoring

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Abstract

Utilization of laser scanning has increased during the past few years in many fields of applications, for example, in road environment monitoring. Mild winters, increasing rainfalls and frost are deteriorating the surface and structure of the road causing road damages. The road environment and its condition can be examined for example with laser scanning and street view images.

Utilization of laser scanning data and street view images in road environment monitoring was studied in this thesis. The main focus was on the road damages and drainage. Also individual trees were detected nearby road scenes. TerraModeler and TerraScan software were used for investigations. Five different lidar datasets were used to detect road damages and drainage. Both mobile and helicopter-based lidar data were available from Jakomäki area. In Rauma case, there were two datasets collected from the helicopter but the point densities were different. In addition, to helicopter-based lidar data, there were also street view images available from BlomSTREET service in Hyvinkää case. The results between the datasets were compared. Aim was to investigate if same damages can be found from the several datasets that have different point densities. Lidar data for individual tree detection was collected by helicopter from Korppoo area. Tree locations were also measured with a tachymeter to get reference data for automatic detection. Heights of the trees were manually determined from the point cloud. Manually measured heights and locations were compared with automatically detected ones.

Detection of rut depths, slopes and drainage is possible from the high point density datasets. From lower point density datasets it is not possible to detect for example rut depths. Point cloud is possible to color by slopes, which may give some information about rut locations even from lower point density datasets. Obtaining slopes and drainage accurately is also possible from lower point density data. With TerraModeler water gathering points can be obtained. Panorama pictures from BlomSTREET can be utilized for ensuring if there is a rainwater outlet or if water will gather as a puddle. Tree locations were detected in a meter accuracy with automatic method. Successful detection of tree heights and locations is dependent on many things. Successful classification of the data and creation of tree models are the most important parameters.

Keywords Individual tree detection, laser scanning, road damages, street view images

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Työn nimi Laserkeilausaineiston ja katunäkymäkuvien hyödyntäminen tieympäristön seurannassa

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Tiivistelmä

Laserkeilaus on yleistynyt ja sitä hyödynnetään useissa eri sovelluksissa kuten esimerkiksi tiesovelluksissa. Leudot ja sateiset talvet sekä routa kuluttavat tien pintaa ja rakennetta aiheuttaen tievaurioita, jotka voivat olla vaaraksi liikenteelle. Tienkuntoa ja sen ympäristöä voidaan tarkastella esimerkiksi laserkeilausaineistojen sekä katunäkymäkuvien avulla.

Työssä tutkittiin kuinka laserkeilausaineistoa ja katunäkymäkuvia voidaan hyödyntää tieympäristön seurannassa. Tutkimuksessa keskityttiin tarkastelemaan tievaurioita ja kuivatusta sekä tiealueiden läheisyydessä sijaitsevien puiden tunnistusta. Tutkimuksessa käytettiin TerraModeler ja TerraScan ohjelmistoja. Tievaurioita ja kuivatusta tutkittiin viidestä eri aineistosta kolmelta eri alueelta. Jakomäen alueelta tien ominaisuuksia tutkittiin sekä mobiili- että helikopterilaserkeilausaineistosta ja Rauman alueelta vaurioita kartoitettiin kahdesta eri helikopterilla kerätystä pistetiheyden aineistosta. Hyvinkäältä helikopterilla kerätyn laserkeilausaineiston lisäksi oli saatavilla katunäkymäkuvia BlomSTREET palvelusta. Aineistoista saatuja tuloksia vertailtiin keskenään ja tutkittiin, onko niistä mahdollista havaita samankaltaisia tuloksia. Yksittäisen puun tunnistukseen käytettiin helikopterilla kerättyä laserkeilausaineistoa Korppoon alueelta ja referenssinä aineistolle toimi maastossa mitatut puiden sijainnit. Automaattisesti määritettyjen puiden sijaintia verrattiin maastossa mitattuihin sijainteihin. Myös puiden korkeus määritettiin pistepilvestä manuaalisesti ja tätä verrattiin automaattiseen korkeuden määritykseen.

Korkean pistetiheyden laserkeilausaineistoilla on mahdollista tutkia tien urautumista, tien kaltevuuksia ja kuivatusta. Matalamman pistetiheyden aineistoista ei pystytä määrittämään esimerkiksi urasyvyyksiä. Pistepilvi on mahdollista värjätä kaltevuuksien mukaan, minkä avulla urautumista voidaan havaita jossain määrin myös matalampien pistetiheyksien aineistoista. Tien kaltevuuksia ja kuivatusta pystytään havaitsemaan tarkasti jopa alhaisista pistetiheyden aineistoista. TerraModelerin avulla voidaan määrittää alueet, johon sadevesi kasautuu. BlomSTREET 360 panoraamakuvien avulla pystytään tarkastamaan onko kohdassa sadevesikaivo vai kerääntyykö vesi lammikoiksi. Yksittäisten puiden sijainnin määrittäminen onnistui noin metrin tarkkuudella, mutta sijainnin ja korkeuden määrittämisen onnistuminen on riippuvainen monesta tekijästä. Pistepilven luokittelun onnistumisen lisäksi yksi tärkeä tekijä on puiden muodoista tehdyt mallit, joiden avulla TerraScan ohjelmisto etsii yksittäisiä puita.

Avainsanat Laserkeilaus, katunäkymäkuvat, tievauriot, yksittäisen puun tunnistus

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Abbreviations

3D	Three-dimensional
ALS	Airborne Laser Scanning
AM	Amplitude Modulation
AVG	Average Daily Traffic
CCD	Charged-coupled devices
CHM	Canopy Height Model
CMOS	Complimentary metal-oxide-semiconductor
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
FM	Frequency Modulation
FOV	Field of View
GNSS	Navigation Satellite System
GPS	Global Positioning System
IMU	Inertial Measurement Unit
ITD	Individual Tree Detection
IFOV	Instantaneous Field of View
LAS	LASer file format for 3D point cloud data
Lidar	Light Detection and Ranging
MLS	Mobile Laser Scanning
MMS	Mobile Mapping Systems
POS	Positioning and Orientation System
RMS	Root Mean Square
PDOP	Position Dilution of Precision
SLD	SLiDe file format for AutoCAD software
TASQ	TopEye Area Statistics and Quality
TLS	Terrestrial Laser Scanning
UAV	Unmanned Aerial Vehicle
WFS	Web Feature Service
WMS	Web Map Service

1 Introduction

1.1 Background

Laser scanning has become more popular in different fields of studies. It is used for example in archeology, construction sites and 3D modeling, just to mention few. Laser scanning is multifunctional technique that can be performed in aerial, terrestrial and mobile methods. This thesis is focusing on study the road environment with lidar (light detection and ranging) data and street view images. Especially mobile laser scanning is widely utilized in road applications.

There are many risk factors in road environment, which can cause unsafe situations in traffic. Four seasons in Finland are causing challenging weather conditions for the road. These changes in weather accelerate the deterioration of the road surface and structure. This is why there are strict regulations for the condition of the road in Finland. Damages and inoperative drainage system can be causing dangerous situations in traffic. Nowadays the methods used for detecting the road damages are rather time consuming and the quality is not homogeneous. Every year, a long section of the Finnish road network is checked, which is why it is important to have an efficient way of detecting the possible road damages.

The largest cities in Finland have started to collect data about trees for the tree registers. This kind of information is useful for example in the maintenance of trees. This way maintenance can be performed more efficiently and some cost savings can be achieved. By detecting individual trees, visibility analysis can also be performed. With this analysis it is possible to see if trees are for example blocking the straight view to the traffic signs. This is one factor affecting the traffic safety.

Helicopter-based laser scanning is a common way to collect data for example for elevation models. If there is this kind of data available, it is interesting to know what other purposes it can be utilized. There are a wide range of opportunities and applications where this kind of 3D point cloud data could be used.

1.2 Objectives of the study

Objectives of this thesis are to investigate if road damages, drainage and individual trees can be detected from helicopter-based lidar data. Focus is in urban areas, where also street view images can be collected. Datasets with different point densities were compared to see if similar results can be obtained. The utilization of street view images, in BlomSTREET service, together with lidar data, when obtaining road damages and drainage, are also studied. Lot of algorithms and methods have been invented for tree detection in forest areas. Therefore, this thesis is focusing on individual tree detection in urban areas and especially on planted trees that are located in road environment. The goal is automatically to detect the locations and heights of the trees.

Is it possible to detect individual trees by using laser-scanned data collected by helicopter? Is it possible to receive information about road damages or road drainage by using the tools of TerraScan and TerraModeler? What are the differences between the lower and higher point density datasets? How can be BlomSTREET utilized with these findings?

1.3 Structure of thesis

This thesis is divided into the literature survey and empirical part. The thesis starts with an introduction to a topic. In addition, the background and objectives of the study is discussed. The principle of the laser scanning is presented in the second chapter. Basic methods for range measurement and full waveform technique are also given. The third and the fourth chapter includes the introduction to airborne and mobile laser scanning systems and process. In Chapter 5, typical road measurement techniques and damage types are presented and in Chapter 6, introduction to individual tree detection methods is given. Material, methods and software used in this thesis are discussed in Chapter 7. The results achieved in this thesis are presented in Chapter 8. Chapter 9 gives the summary and conclusion to the study.

2 Principles of laser scanning

2.1 Lidar

Light detection and ranging (lidar) is the technique behind airborne laser scanning (ALS) (Kukko 2013, p. 17). When talking about laser scanning it is important to know the principle of the laser. The characteristics of the laser light, makes it suitable for range measurement. The laser is coherent, monochromatic, and easily aligned in one direction, which means that the velocity of the emitted pulse stays constant. Lasers, used in laser scanners, are not generally damaging to the human eye. (Wehr & Lohr 1999, p. 69-70; Vosselman & Maas 2010, p. 12, 26.) In terrestrial laser scanning (TLS), it is recommended not to look directly to the laser scanner, when the scanning process has started. All RIEGL's mobile laser scanners are using Class I lasers, which means that it is the safest laser in use. Some of the lasers that are used in RIEGL's airborne laser scanners are classified to Class I but some of the scanners are using Class 3B or 3R. These are harmful, if the laser beam is directly pointing or reflecting from a smooth object to the eye. Because the aircrafts and helicopters are flying rather high, in a certain distance Classes 3B and 3R are safe for the naked eye. Nowadays the power of a laser pulse is changeable. (RIEGL 2014; U.S. Department of Energy 2015.) For example, when calculating values with Leica's flight planning software called Leica Mission Pro for Leica's ALS60 laser scanner, the flying height is 2501 meters and laser pulse rate 95400 Hz, the laser is eye-safe for a naked eye 261 meters below the aircraft and for binoculars it is eye-safe 1686 meters below the flying height.

Laser scanning is a method used by airborne, mobile and terrestrial laser scanners. Laser scanning systems are able to collect data from objects and sites producing 3D point cloud data contact-free. Scanners can obtain even hundreds of thousands of points in one second. These systems are measuring the range by transmitting laser beams and receiving the reflected beam. This means that laser scanner is an active instrument and it can be used during day and night. (Vosselman & Maas 2010, p. 1; Wehr & Lohr 1999, p. 68.) With laser scanning technique, georeferenced point clouds can be produced (Kaartinen et al. 2013, p. 51). Nowadays most of the scanners are able to record several backscattered echoes and even full waveform (Mallet & Bretar 2009, p. 3). Laser scanner detects only one echo, when the emitted pulse hits straight to plain objects such as rocks and buildings (Schuckman & Renslow 2009). In cases of this kind, multiple echoes are not needed to collect but usually there are more objects on the way of a laser pulse, for example building edge may cause two or more echoes when the laser beam hits on the roof and part of the beam continues and hits to the ground (Mallet & Bretar 2009, p. 3). Because of the site features, like vegetation, the emitted laser beam usually records multiple echoes (Vosselman & Maas 2010, p. 3). Few first collected echoes are the strongest ones containing almost all the power of the emitted laser pulse (Mallet & Bretar 2009, p. 3). When doing the post processing for multiple echoes, it is possible to receive precise information about the ground surface and objects above ground such as vegetation. Downside is the increasing amount of the data, which makes the software work slower. (Schuckman & Renslow 2009.) Most of the laser scanning systems are capable of obtaining reflected energy of the object or site. This kind of data is called intensity data and it is useful for example when detecting road paintings. (Kukko et al. 2012, p. 11716.)

2.1.1 Range measurement

Most of the airborne laser scanning systems use laser scanners that are based on time-of-flight (ToF) techniques, to measure the range. Two main methods are rather similar because both techniques determine the travelling time of the laser beam but they are using different ways. One method uses the pulse and the other method is utilizing the phase difference to determine the range. (Wehr & Lohr 1999, p. 70; Vosselman & Maas 2010, p. 4-6.) Pulse technique measures the range using the information about the velocity of the light. Time of flight is the time between emitted and received pulse. This technique uses short laser pulses and it measures the time of the round trip from the scanner to the object and back. (Kukko 2013, p. 27; Mallet & Bretar 2009, p. 2; Wehr & Lohr 1999, p. 70.) When the laser scanner is using pulse technique, simple way to measure the range is to use equation (1.1). Speed of flight c and the correction factor for air n are known constants and τ is the round trip from the scanner to the target and back. The round trip has to be divided by two to obtain the one-way distance from the scanner to the object or site. This method is more common in airborne laser scanners. (Vosselman & Maas 2010, p. 3, 7.)

$$\rho = \frac{c}{n}\frac{\tau}{2} \qquad (1.1)$$

Phase measurement techniques for continuous wave ranging are using phase difference, frequencies, phase-coded compression or waveforms to measure the traveling time. Emitted laser light is first modulated so that the phase difference can be exploited. Amplitude modulation (AM) is the most popular method utilized in phase measurement techniques. It uses phase difference for range measurement. It compares the transmitted and received phase of laser beams with each other. AM often uses multiple frequencies. It is possible to achieve better results and greater distances when multiple frequencies are used. The frequencies must be known because the shortest wavelength gives information about accuracy and the longest about the maximum range. Frequency modulation (FM) is also a phase measurement technique. In this method, the modulation for the laser light's frequency can be done with linear modulation. These phase measurement techniques are more common in terrestrial laser scanners. Beside previous techniques, laser scanners can utilize triangulation for range measurement but it is mostly used to measure small objects from a short distance. This method is utilized for example when quality conformance inspection is made for industrial components. (Wehr & Lohr 1999, p. 71-72; Vosselman & Maas 2010, p. 5-8.)

2.1.2 Full waveform

Full waveform is using pulse technique. This method is able to store and digitize the complete information about the returned pulse (Vosselman & Maas 2010, p. 28). The principal of the full waveform is presented in Figure 1, before (blue) and after (black) digitization. Figure 1 shows how the scanner records several echoes. For example, the first echo will hit the top of the tree and the last echo to the ground surface. This is why it is possible to create both surface and canopy height models. The amount of the data required increases using this technique due to recording the entire waveform. This must be taken into account when thinking about data processing. (Schuckman & Renslow 2009; Kukko 2013, p. 32.)

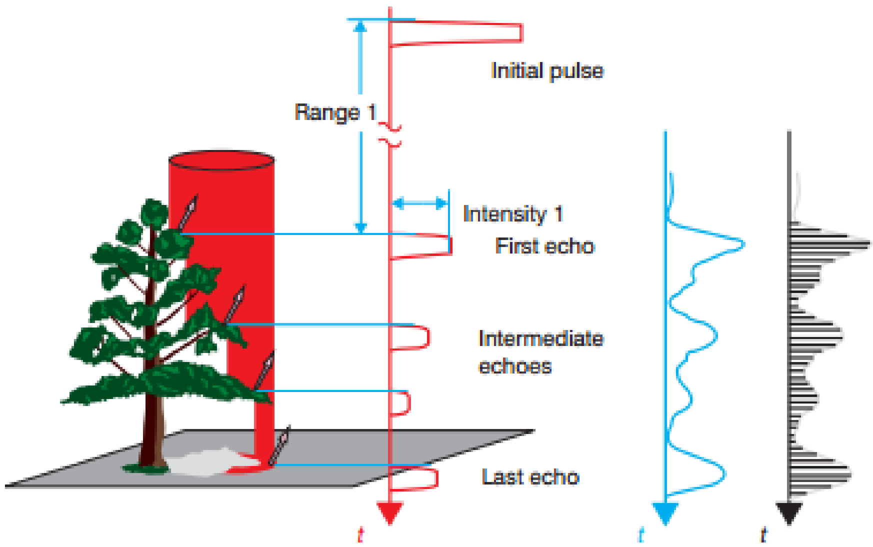

Figure 1: Principle of full waveform (Vosselman & Maas 2010, p. 29).

Full waveform technique has brought new possibilities for several applications. It is useful especially in forestry and vegetation applications because of its ability to record the full waveform from the ground to the top of the tree. It can obtain horizontal and vertical information about the structure of the vegetation. It gives a convenient way to estimate, for example steam volume. (Fieber et al. 2013, p. 64; Heinzel & Koch 2011, p. 152.) Full waveform enables more opportunities for the post processing and interpretation of the data because there is more data available. On the other hand, the amount of the data greatly increases and data reducing might be necessary. Some preprocessing is required to get the needed information out of the data. Full waveform systems may differ and it depends on the surveyed area and the final product which kind of system is the best to use. Footprint size, repetition frequency and pulse energy may vary. Most of the commercial systems offer high point density and systems have a small footprint. The size of the footprint depends on the flying height and beam divergence. Large footprint systems use higher energy and lower frequencies compared with the small footprint systems. Systems that have a large footprint are more likely able to collect data from both tree canopy and ground surface. The distance, from a laser scanner's platform to the ground, and beam divergence are factors affecting the size of a footprint. (Mallet & Bretar 2009, p. 4-6.)

According to article written by Mallet & Bretar (2009, p. 5-10) when classifying full waveform data, sometimes it might be difficult to know, if the laser beams have actually reached the ground or if they hit low vegetation. If data is collected with full waveform scanners, it may help when the post processing is done, for example segmentation. Classification is trickier if compared with the normal laser scanned 3D point cloud. There is more data available and the differences between classes might not be unambiguous. If most simple algorithms are exploited, there is a large risk for incorrect classification. Typically, characteristics of echoes and amplitudes give a hint about the measured objects. The materials of the objects may still differ which makes the classification challenging. The back scattering coefficient and the cross section can help to give better results. The main advantages using full waveform are in forest and vegetation areas but it is also useful in urban areas and for example building materials can be detected visually.

3 Airborne laser scanning system and process

3.1 Components of airborne laser scanning system

Airborne laser scanning is a term given when the used platform is an airplane, helicopter or unmanned aerial vehicles (UAV). Nowadays, UAVs are commonly used as a platform for laser scanners. First, the principal components are described including the scanner, camera and positioning system. The airborne laser scanning system includes the laser scanner that is for range measuring and global positioning and the inertial measurement unit (GPS/IMU) -system that determines the orientations and positioning. These are the main elements in the ALS system. In addition to the main components, airborne systems typically have a camera, a control and data recording unit, an operator laptop and a flight management system. Cameras shoot pictures during the scans, which is beneficial when processing the data. (Baltsavias 1999b, p. 168; Vosselman & Maas 2010, p. 21-24.) Nowadays, the cameras are aerial cameras so images can be utilized for example orthophotos, oblique aerial imagery and other applications.

3.1.1 Laser scanner and digital camera

Laser scanner measures the range and there are several methods of measuring the distance as shown above. The laser scanner system includes three main elements: the control processing unit, the opto-mechanical scanner and the range measurement unit. (Schuckman & Renslow 2009.) The laser has a limited instantaneous field of view (IFOV), which means that the emitted laser beam has to be moved to cover an object or a site (Wehr & Lohr 1999, p. 69). This can be done by using mirrors. Movement of a vehicle is utilized, except in terrestrial laser scanning (Vosselman & Maas 2010, p. 16).

The optical domain is typically used in ALS systems (Ahokas 2013, p. 17). The site characteristics and project determine which wavelength (normally between 800-1550 nm) should be used. When the laser scanning is done in reflecting areas, shorter wavelengths are more beneficial. (Wehr & Lohr 1999, p. 74; Vosselman & Maas 2010, p. 25.) Scanners using optical wavelengths are normally not able to collect data from water areas. Swamps, flooded fields and water on roads might cause gaps to the point cloud data. Airborne lidar bathymetry is a method that is able to collect point cloud data from the water surface and below it. This system is using two different wavelengths, one is infrared (1064nm) and the other is green (532 nm). The green laser is able to penetrate the water surface and measure the seabed to a certain water depth, depending on water clarity. Infrared lidar is able to obtain the water surface and the range from the surface to the platform. The difference between normal airborne laser scanning and airborne lidar bathymetry is that lidar bathymetry requires higher energy. (Vosselman & Maas 2010, p. 25, 35-36.)

In Figure 2, several scanning mechanisms are presented but ALS systems mainly use either oscillating mirror (Figure 2a) or rotating polygon mirror (Figure 2b) (Ullrich et al. 2013, p. 2). Scanners usually have a mirror that can move the laser beam in a different directions and this determines the field of view (FOV). A rotating polygonal mirror is one type of mirror and it can achieve scanning angle between 30 and 60 degrees. (Vosselman & Maas 2010, p. 16.) For example, most of the RIEGL's airborne scanners are using this mechanism (RIEGL 2014). The oscillating mirror is sweeping sideward and the other direction is the movement of the helicopter forming a zigzag-pattern (Vosselman & Maas 2010, p. 16). Due to the changing velocity of the oscillating mirror, the point density differs directly under the aircraft and at the edge of the swath where the density is higher (Schuckman & Renslow 2009).

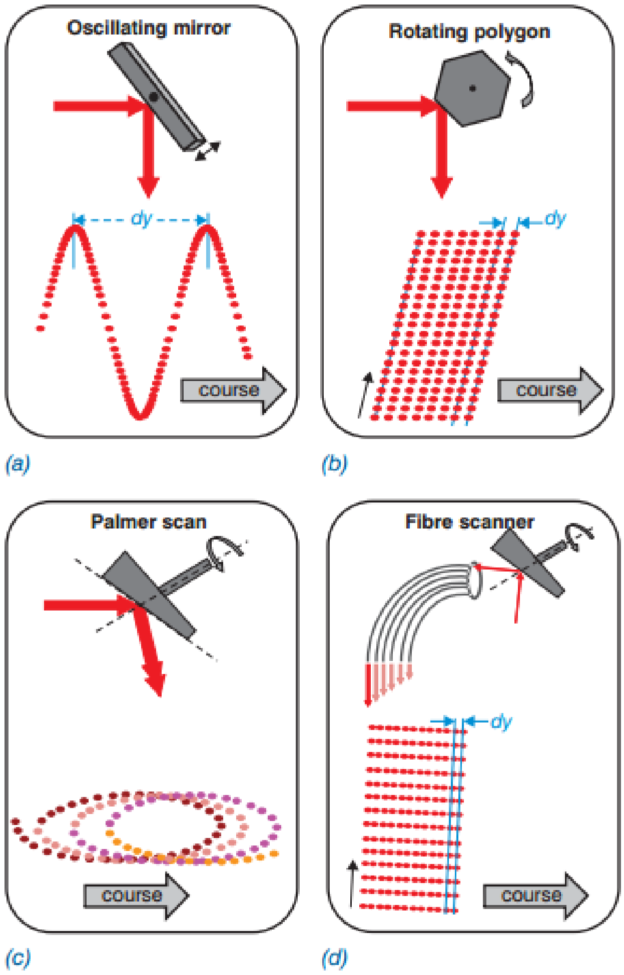

Figure 2: Four main scanning mechanisms and formed scanning patterns (Vosselman & Maas 2010, p. 17).

The field of view (FOV) can be modified but scanners have a limiting maximum field of view. Palmer scanners (Figure 2c) are more common in terrestrial systems but are sometimes used in airborne systems forming elliptical scanning pattern. A glass fibre scanner (Figure 2d) provides a scan angle of 14 degrees. (Vosselman & Maas 2010, p. 16.) The final scanning pattern depends on the surface and flying parameters such as the direction and speed (Wehr & Lohr 1999, p. 76). Other types of mirrors can also be utilized. Transmitted laser beams deviate differently depending on the technique used (Kukko 2013, p. 28).

Aside from range, lasers are able to record the intensity from the reflected pulses. Intensity presents, how strong the returned pulse is and how strong is the reflection of the object or site. Intensity may support data processing such as classification and visualization. (Wehr & Lohr 1999, p. 81.) Utilization of intensity has increased significantly in post processing of laser scanning data in recent years. It is possible to plan and compute some of the scanner parameters when the project need are known. For example, Leica's ALS60 airborne laser scanner operates at a flying height of 2501 meters above ground level and can provide 40 degrees field of view with about 1820 meter long full swath width. Values are calculated with Leica's flight planning software, Leica Mission Pro.

Usually, the laser scanning system includes an aerial camera. The camera is capturing images during the survey flight. Photographed images may help in the interpretation of the data. There are some practicalities when using both a laser scanner and a digital camera on the same platform. Digital camera needs an extra hole to the platform and it increases the total weight. Flight parameters have to be taken into account that both laser scanner and digital camera are under consideration. (Vosselman & Maas 2010, p. 23, 34.) On the other hand, when both scanner and camera are mounted on the helicopter or aircraft, it is possible to achieve some cost savings. It is more expensive to fly the same area twice than fly once with both instruments mounted when both sets of data are required.

3.1.2 Positioning

Laser scanning systems require position and orientation information for producing accurate data. An airborne laser scanning system requires POS that is the position and orientation system. This system should provide the same level accuracy as the range measurements. By using IMU and GPS, it is possible to detect the exact position and movement of the aircraft. Continuous information of position and orientation is highly important otherwise, it is impossible to determine the position of the 3D-points. (Vosselman & Maas 2010, p. 23-24; Wehr & Lohr 1999, p. 78.) IMU measures the position and the orientation (yaw, pitch and roll) of the aircraft. In addition, it obtains the acceleration of the platform using accelerometers. It is possible to increase accuracy of IMU data when updating it with GPS position data. With information obtained from IMU and GPS it is possible to recreate the trajectories with accuracy of 10 cm. (Vosselman & Maas 2010, p. 23-24.)

GPS is a satellite navigation system that originates from the USA and it was created for military services (National land survey of Finland 2014). The GPS system determines the X, Y and Z-coordinates during the scanning (Schuckman & Renslow 2009). In addition to the GPS there are several satellite systems becoming available and the term, global navigation satellite system (GNSS) can be used. The Russian GLONASS system is already partly operating. European Galileo and Chinese Compass systems are in progress. (Blázquez & Colomina 2012, p. 120.) The positioning system includes the GPS ground stations that should be located close to the scanned area, no further than 30 km from the helicopter. Nowadays, virtual stations can also be used. Data from the stations can be utilized to calculate differential global positioning system values (DGPS) that are correcting the errors caused by the atmosphere. These ground stations make it possible to get more accurate positioning for the helicopter. (Vosselman & Maas 2010 p. 23; Leica Geosystems 2015.)

Direct georeferencing makes it possible to receive 3D point cloud data. GPS and IMU systems are the main elements in the process. By combining the results from the GPS and IMU, absolute orientations and vector attitudes are available. (Mallet & Bretar 2009, p. 2-3.) Direct georeferencing can be done by using GPS and IMU system. It means the determination of the roll, pitch, yaw (orientation) and scanner position with X, Y and Z – coordinates. (Schuckman & Renslow 2009.) All the data from IMU, GPS and laser scanner must be able to integrate for further data processing. The control and data recording unit stores the time information about individual systems. This unit is used to manage the system. Time tags are one option for merging the point clouds with calculated and corrected trajectories. (Vosselman & Maas 2010, p. 23-24; Wehr & Lohr 1999, p. 78.) Integrated GPS and IMU data enables direct georeferencing (Schuckman & Renslow 2009).

3.2 Helicopter-based laser scanning process

Low altitude (helicopter-based) and fixed-wing aircraft laser scanning are efficient ways to collect data with high accuracy. These methods are quite similar to each other. Scanning is perpendicular right under the platform and usually scanning angle is rather small. The main difference is the flying altitude. Helicopters are able to fly at lower altitude and with slower velocity. (Schuckman & Renslow 2009.) Helicopter-based laser scanning is normally done when the mapping area is rather small. Suitable sites are, for example long and narrow areas such as power lines, road scenes or coastlines. Helicopter laser scanning is convenient especially when higher accuracy and point density is required. This is possible due to lower altitude and flying speed. If higher point density is needed, the scanning angle may be reduced and higher pulse repetition frequencies can be utilized. (Baltsavias 1999b, p. 168; Vosselman & Maas 2010, p. 27.) Flight trajectories are possible to recreate using GPS and IMU systems. Recreated trajectory information is required in the data processing. (Vosselman & Maas 2010, p. 23.)

3.2.1 Survey planning and data collection

The laser scanning project normally starts with flight planning. With low altitude scanning, it is possible to follow quite accurately corridor-like areas such as highways. Flight planning is important step of the project because it always depends on site and customer's needs. Flight planning is done in such a way that it covers the entire area with the necessary overlap of flight lines. At least one cross line is needed for each block to control the accuracy. The customer's needs define the specifications for the project. These specifications include the velocity of the helicopter, flying altitude and scan angle that affects the point density and swath width. (Vosselman & Maas 2010, p. 30.)

Certain system calibrations are needed to ensure that there are no errors in the system. First calibration for the sensor system is performed at the factory and it is called laboratory calibration. This calibration is executed again only if changes have been made to the system or the system is damaged. Calibration of the lidar sensor system has to be checked whenever it is moved or installed again inside the helicopter or aircraft. This is carried out by field-testing where calibration targets have been set and surveyed at the calibration site. The aircraft flies over the calibration area and finally the results are compared with each other. (Schuckman & Renslow 2009.)

After flight planning, the next step is the survey flight. In Figure 3, is presented the basic principle of airborne laser scanning. Scanning angle and already covered areas are marked with the red color. Time of the survey flight depends on the weather and project details. It is not possible to collect data when it is raining or when there is fog or many clouds. Purpose of the project determines what time of the year the scanning is carried out. If the purpose is forestry, usually the leaves are on. Laser beams are in most cases capable of penetrating the crown canopy especially when using full waveform technique. However, the view to the ground surface is better when the leaves are off. When the aim is to model the surface, it must be done when there is no snow on the ground. Usually few centimeters of snow has no effect when modeling a surface, if the laser scanner is able to obtain points from the snow. (Vosselman & Maas 2010, p. 31-32, 35.) According to Ahokas (2013, p. 14) the scanning angle is important to take under consideration especially, when laser scanning is performed in forested areas and the final product is an elevation model. By changing the scanning angle, the laser pulse is penetrating more easily through the canopy.

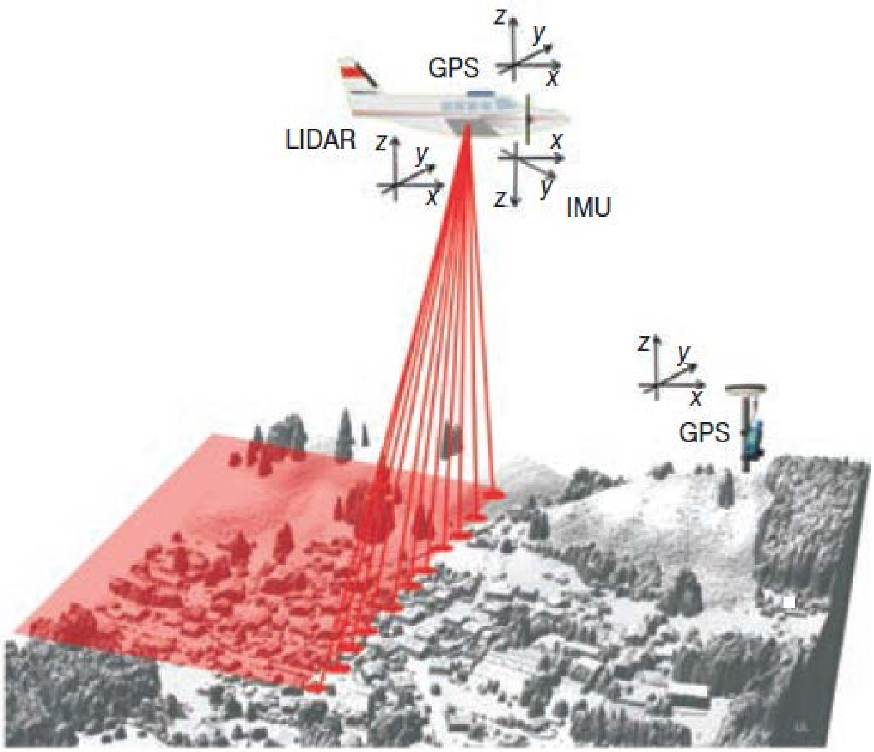

Figure 3: Airborne laser scanning survey flight (Vosselman & Maas 2010, p. 21).

Point density depends mostly on the velocity of the aircraft, flying altitude and scanning angle. The density is higher if the parameters are smaller. Point density in the scanned area is not uniformly distributed. The scanning pattern of the scanner and surface topography are some of the reasons, which affect the variation of the point distribution. The fast development of the instruments allows higher point density from the same flying altitude. (Vosselman & Maas 2010, p. 27.)

GPS ground stations are important part of the survey flight (Vosselman & Maas 2010, p. 32). In Finland, there are two virtual ground station networks available; one is provided by Trimble (Trimnet) and the other by Leica (SmartNet). It is possible to use these networks simultaneously. These stations are about 20-30 km away from each other. Usually, the goal is to place the survey area inside a polygon, which is formed by four ground stations. Next to the border areas of two countries, this might cause some problems if there is no information about the ground stations of neighboring countries. When a single GNSS base station is used in a survey flight, every three hours the aircraft or helicopter must fly above the ground station. (Blom Geomatics AS 2011; Leica Geosystems 2015.)

Before the helicopter or aircraft is on the survey area, it has to do IMU turns, to start it to work properly. Blom Geomatics AS (2011) has its regulations for flight procedures for data capture, for example IMU turns must be done, when mission altitude is achieved. In Figure 4, are some examples how to perform the IMU turns. Minimum demand is at first to turn 180 degrees and then 90 degrees to the other direction. Trajectories cannot be longer than 20 minutes or 50 nautical miles, otherwise IMU errors start to increase. If position dilution of precision (PDOP) increases too much, the trajectory must be re-flied.

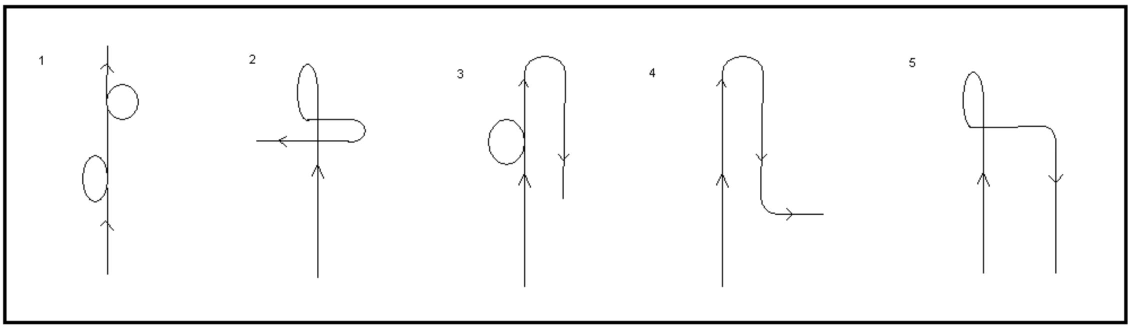

Figure 4: IMU turns (Blom Geomatics AS 2011).

3.2.2 Data processing

Airborne laser scanning projects have many things that have to be taken into account. The main steps are flight planning, survey, data processing and quality control. After the survey, the project includes three datasets. There are ground station data from GPS or GNSS and IMU data from the helicopter and amplitude data, echo counts, ranging data and scanner parameters. When the survey flight is flown, positioning data and point cloud data are available. Positioning data includes data from the GPS ground stations, airborne GPS and IMU. Point clouds have the information on how many echoes each transmitted laser pulse has, what were the scanning angle and other scanner parameters. First step is to make the corrections to the GPS data using data from the GPS base stations. After the corrections are checked, it is possible to merge the corrected GPS data and IMU measurements. In addition, calibration data is required. With the help of GPS and IMU data, it is possible to reconstruct the trajectories. Recreated trajectories and measured point clouds can be merged with time tags. The processing needs of a point cloud depends on the final product. Usually at least some kind of classification is needed. (Vosselman & Maas 2010, p. 30, 32.)

Ground checkpoints are needed to observe the deviation between the 3D point clouds and ground truth data (Schuckman & Renslow 2009). Large flight areas not necessarily require that many ground points, which also decreases terrestrial work (Vosselman & Maas 2010, p. 35). Laser scanning data from each scanned line is usually processed to LAS-format. When the 3D point cloud data is available, it is necessary to check the quality of the data. If there are some major problems such as large gaps, the area must be flown again. It is more convenient and cheaper if the aircrafts are still in the area. This is why the quality control should be done as soon as possible after receiving the point cloud data. (Schuckman & Renslow 2009.)

The data must be checked if there are any gaps in the data. Flight lines have to have enough overlapping to achieve required coverage. In addition, echoes, elevations and intensity should be controlled. Quality control is important to carry with throughout the entire process. Errors can be allocated at early stage of the process, which makes the whole process more efficient. (Schuckman & Renslow 2009.) The size of the point cloud data is usually quite large but it still should easily be transferred and stored. This is why the data has to be compressed somehow to get the amount of the data smaller. Hierarchical representation is one convenient way for the compression. (Vosselman & Maas 2010, p. 75.) When the post processing is done, it is reasonable to divide the point cloud data into blocks and process the data separately for every block. This way the software is able to run the functions faster.

3.2.3 Accuracy and error sources

The total accuracy has many parameters that have to be considered reaching the best possible result. These factors include the coordinate system transformation, range accuracy, laser beams positioning and direction. Coordinate system transformation is needed if the result needs to be in a local coordinate system. Different types of data come from different sensors and the data types must integrate. Misregistrations coming from integrating the data sets affect the final accuracy. (Baltsavias 1999a, p. 207.) As said above quality control is important throughout the process to achieve good final accuracy. Quality control helps to detect and remove the errors at early stage of the process. (Schuckman & Renslow 2009.) Many random and systematic errors affect the final accuracy (Habib et al. 2009, p. 1095). Systematic errors may appear either in the 3D point cloud or in the system parameters.

Position accuracy depends on the errors of the POS system. There are several parameters such as atmospheric errors and poor satellite geometry increasing the errors in the positioning system. These kinds of errors are tricky because they are hard to predict and the usage of error models is not straightforward. (Glennie 2007, p. 150.) GPS or GNSS and IMU system's calibration might cause errors as well as reconstructed trajectories. Challenging sites and targets might produce error to the plane surface. (Vosselman & Maas 2010, p. 29.) If the DGPS values are post processed well, the total position accuracy is better. Attitude accuracy is highly dependent on position accuracy. Higher-flying height and a larger scanning angle are affecting the attitude errors. (Baltsavias 1999a, p. 209.)

Reasons for range accuracy differ depending on whether pulse or continuous wave technique is used. Errors in phase technique are related to the time synchronization and errors in the continuous wave method are mostly caused by modulation. Mirrors and optical windows are causing errors for both methods. Time offsets are one factor affecting the total accuracy. Different instruments are used in the laser scanning process. The successful integration of the data sets is critical when trying to achieve good total accuracy. (Baltsavias 1999a, p. 207-209.) IMU attitude, boresight, lever-arm offset, positioning and laser scanner are typical factors causing errors in the scanning process (Glennie 2007, p. 148-150).

4 Mobile laser scanning system and process

4.1 Components of MLS system

Basic components are same in both ALS and MLS systems. The systems include three main elements the scanner(s), camera(s) and positioning system. The number of instruments and used techniques may differ. The principle and the components of mobile laser scanning (MLS) are presented in this chapter to get information about the system and the main differences between ALS and MLS techniques. Mobile laser scanning (MLS) has many similarities compared to airborne laser scanning. MLS is suitable for several different kinds of areas for example small areas and long objectives such as different kinds of road scenes. It is convenient especially in cases where the objects are out of ALS's reach. (Kukko 2013, p. 19, 24; Kukko et al. 2012, p. 11713; Vosselman & Maas 2010, p. 294.)

4.1.1 Laser scanner and digital camera

Most MLS systems use 2D laser scanners but due to the vehicles movement it is possible to obtain the data in 3D. Some of the 2D scanners are providing full 360 degrees FOV. (Kukko 2013 p. 44.) The characteristics of laser scanners depend a lot on of suppliers, for example, a field of view might vary. RIEGL, Optech and SICK are some examples from suppliers that manufacture mobile laser scanners. (Petrie 2010, p. 35-36.) The rotating polygonal mirror is a common scanning mechanism in mobile scanners (Graham 2010, p. 223). Scanners usually stop shooting the laser beams when the vehicle pulls up for example to the traffic lights. The point density is steadier and the amount of the data do not increase that much.

The mobile mapping systems include digital cameras, which are supposed to take frames based either on distance or on time. These cameras are typically digital frame cameras that are different in comparison with the aerial cameras. It depends on the system how many cameras have been mounted to the vehicle. Usually, there are four to eight cameras mounted on a vehicle. The cameras use CCD (charge-coupled devices) or CMOS (complimentary metal-oxide-semiconductor) imaging sensors, which take panoramic pictures that horizontally form full 360-degree picture. This way it is possible to cover the measured area also with pictures. Cameras are able to take frames simultaneously with other cameras. Images taken from the surveyed area increase the final amount of the data. There are several suppliers to such cameras that can be used in MLS systems. (Petrie 2010, p. 32.)

4.1.2 Positioning

MLS systems use GPS and IMU technology to measure the vehicles positioning and orientations as in ALS systems (Vosselman & Maas 2010, p. 294). GPS receivers are able to get the positioning with a few centimeters accuracy if at least four satellites are visible. Tunnels, forested and urban areas cause some problems detecting signals from the satellites. In Figure 5, is presented the mobile laser scanning system that is collecting data. Tall buildings may cause some gaps to positioning data because of the poor satellite visibility, in Figure 5. If there are not enough connections between GPS and the satellites, GPS is not able to get the positioning at all or the accuracy is poor. (Kukko 2013, p. 33.)

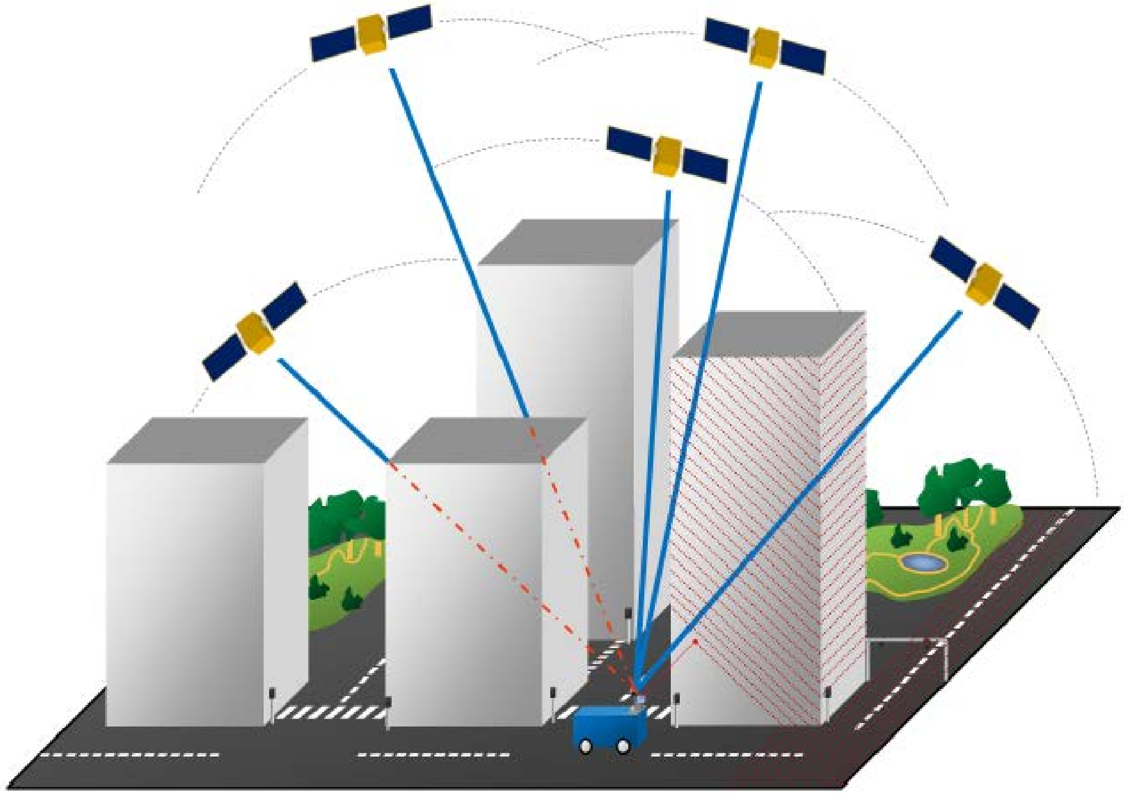

Figure 5: MLS system collecting data in urban area (Kukko 2013, p. 25).

IMU is the primary element in the position and orientation system (POS). It is possible to define the exact location and orientation of the used platform, which is important especially in this case because the platform is moving during the scanning. (Graham 2010, p. 223.) IMU can be used to improve the measurement density. IMU is able to produce precise positioning but if there are no connections to the satellites, it can do it only in the short run. (Barber et al. 2008, p. 130.) Over the time, the errors in positioning increase because of the errors in the gyroscope and accelerometer. In addition to the GPS and IMU, the mobile mapping system, has an odometer wheel. When there are no satellites visible, IMU and odometer wheel are capable of determining the positioning. Corrections to errors can be made using the GPS data. The positioning system includes several sensors that are mounted on the platform and data from these sensors have to be able to synchronize. The system has its own local coordinate frame and it can be transformed to another coordinate system. (Kukko 2013, p. 33, 38; Petrie 2010, p. 37.)

4.2 MLS process

The MLS process has many similarities with ALS process. It starts with planning the whole process. If possible, problematics are taken into account, to avoid errors and achieve better accuracy. After the planning step, data collection can be made. At this point, there are several datasets available that have to be synchronized and post processed. MLS is providing high-speed and high-resolution 3D data. MLS is a faster way to capture data from large areas when comparing with terrestrial laser scanning (TLS). MLS has the safety aspects for example in areas where there is heavy traffic. Cars and vans, in which laser scanner is mounted, are able to drive along with other traffic. Workers do not have to stand in the middle of the traffic lanes causing dangerous situations. Vans and cars are good examples and mostly used as laser scanner's platforms. Vehicles provide enough space to mount all needed instruments. Nowadays, boats and humans are also used as a platform. TLS has its own applications where it is more suitable. (Kukko et al. 2012, p. 11713-11714, 11716.)

4.2.1 Planning and data collection

Process planning is highly important in both the ALS process and in the MLS process. Data that is more accurate can be provided if the planning step is carefully carried out. Especially GPS planning is significant because in some cases augmented GPS might be needed. Survey area must be checked if there are areas where there is possibility for loss or weakening of the GPS signal. Tunnels and urban areas with high buildings might be such areas. Depending on the final product and its needs, each parameter has to be planned carefully before hand to achieve the ideal result. Speed of the platform, mount angle of the scanner, velocity of the spinning scanner and pulse repeatability rate are parameters that have to be taken into account when planning the scanning process. It is important to check the weather before the scanning is started. Wet pavement may cause some gaps when collecting 3D point cloud data from the road scene. (Graham 2010, p. 223-225.)

Calibration is important part when trying to achieve the best possible result. Every instrument has its own period of time when the instrument should be calibrated. However, when there are any changes happening in the system, calibration needs to be redone. A mobile mapping system includes two scanners and at least two cameras. This means that the calibration is performed separately for every sensor. (Graham 2010, p. 225.) Measured point density depends on the velocity of the used vehicle. With lower velocity, the point density is higher. Range to the object or site, overlapping scans and sensor's height are affecting the point density. Point density is determined depending on a purpose of the final product, which affects the project planning. If the project requires high point density then the area might have to be driven more than once. Overlapping scanning lines are beneficial for the MLS projects. Those increase the final accuracy of the processed point cloud data. (Hunter 2007, p. 180, 183.)

Mobile mapping can be done either stop-and-go mode or on-the-fly mode. This thesis is focusing on on-the-fly-mode. Stop-and-go mode merges terrestrial and kinematic laser scanning methods. Stop-and-go mode uses vehicles for example vans, autonomous vehicles or robots as a platform. Vehicles are chosen depending on the use, for example, different vehicles are used indoor and outdoor purposes. The vehicle changes its position between the scans but during the scan, it stays still which means that scanner's orientation and positioning do not alternate. On-the-fly mode the platform is moving and the laser scanner is collecting data continuously. (Vosselman & Maas 2010, p. 295-296.) Each measured point is in the coordinate frame of the platform. Usually the images and point clouds are transformed to a local coordinate system. (Kukko 2013, p. 38.) Before the vehicle starts the survey, it has to stay still for five minutes to synchronize the position of the IMU and GPS. The similar stop has to be done after the survey. (Puente et al. 2011, p. 165.)

4.2.2 Data processing

Data processing is similar with airborne laser scanning because it has the same main data sets: point cloud data, IMU and GPS data and imagery. The mobile mapping system (MMS) process usually consists of four main parts. The first part is imaging. The second part is referencing which can be divided into two different parts, spatial and temporal. Third part includes communication and process control. Final part discusses the data processing and product supply. (Vosselman & Maas 2010, p. 298.) Raw data is normally in a format provided by the manufacturer. The data and its parameters have to be processed usually to LAS-format (file format for handling 3D point cloud data), which is the same in ALS. (Graham 2010, p. 225.) Data processing starts by computing the trajectories of the vehicle from IMU and GPS data. After this step, the corrected trajectories are available. Synchronization of all data, measured by various instruments, is necessary for post processing. (El-Sheimy 2005, p. 2.)

Classification of the lidar data is the main step in the data processing. Data can be classified in to different classes, using automatic tools, provided by commercial software such as TerraScan by TerraSolid. The points are classified to certain classes depending on what kind of object the points are reflected from. Lidar data can be divided for example to ground, water, low vegetation, high vegetation and building -classes. This step assists the workflow when using the data later on. This is similar to ALS data processing but there are still some differences. Especially the used algorithms differ much because significant objects are different when observing with a helicopter or with a car. Pole-like objects are, for example, more common in MLS data than in ALS data. Automatic classification is prone to errors, which is why manual work is needed to correct the errors made by the automatic classification. (Graham 2010, p. 227; Soininen 2014, p. 397-428.)

4.2.3 Accuracy and error sources

Accuracy and error sources are rather similar with ALS error sources. Accuracy of the MLS system is highly dependent on the visibility of the satellites and GNSS signals. Low visibility is common especially in urban and forest areas because of the high buildings and trees. In addition, tunnels and bridges cause problems since there is a chance for losing the GPS signal. After such a loss, it is recommended to stop the vehicle in open area for the system to fix positioning. Some corrections can be done using IMU and odometer. (Kaartinen et al. 2013, p. 52; Grierson 2014.) Geometric correction is performed by using surveyed control points to fix geometric errors in the lidar data. It is necessary to check the quality of the data several times during the process in order to remove errors immediately after detecting one. Quality control makes it possible to get rid of the gross errors. (Graham 2010, p. 226-227.) Other vehicles affect the point density if they are blocking the straight view from the scanner to the object or site. This is why the scanning should be performed when there is no heavy traffic if it is possible. (Grierson 2014.)

5 Comparison and combination of ALS and MLS data

Both helicopter-based and mobile laser scanning methods have their own benefits depending on the usage and the final product. Mobile laser scanning is more prone to positioning errors but on the other hand, the point density is higher than from the airborne laser scanner. In ALS, the visibility to the satellites typically stays rather consistent but in MLS, the satellite visibility is not as good. It varies more due to high buildings, vegetation and other built-up environment. (Grierson 2014; Vosselman & Maas 2010, p. 23-24, 294; Wehr & Lohr 1999, p. 78.)

Mobile laser scanning vehicles are limited to use only a road network or depends in which platform the scanner is mounted (a van, a boat, etc.) while flight planning for helicopters is not tied to, for example, road networks. Helicopters are able to fly at constant speed but vehicles have to take into account the traffic and traffic regulations, which causes point density and velocity changes. Scanners that are mounted into a helicopter are able to collect points fast with a rather smooth point density. Mobile laser scanners can obtain more points on the traffic lanes than off the road, which means that, the point density varies. For example, ground points are hard to detect from areas that are next to the streets due to the shadow area. In Figure 6, is presented a cross section from MLS data. It can be seen that there are not many points obtained from slope in Figure 6. MLS systems can obtain higher point density from objects and sites, which are close and visible to the scanners. It is hard to get a walk-through view from the airborne laser scanned data but with a mobile system, it can be made. (Grierson 2014.)

It is possible to combine the data, if there is data available from the both helicopter-based and mobile systems. Merging helicopter-based and mobile data with each other enables the utilization of both dataset's best features. In Figure 7, are presented both ALS and MLS points, it is possible to see that there are ground points in ALS data but not that much in MLS data when investigating off road area. This way it is possible to achieve maximum coverage for the whole road scene. Airborne systems are able to collect points from vegetation, ground, the edge of the road and lateral ditch while mobile systems are obtaining dense point cloud data from traffic lanes. Shadow areas are larger if there are, for example, fences or deep lateral ditches beside of the road. (Grierson 2014.)

Figure 6: Cross section of mobile laser scanning data (Grierson 2014, p. 38).

Figure 7: Cross section of combined ALS (white) and MLS (colored) data (Grierson 2014, p. 38).

Combined dataset could be utilized, for example, in individual tree detection. Mobile laser scanning systems can obtain more points from tree trunks and the ALS systems can collect more points from tree crowns. With combined data set, clear tree shapes can be detected. Collecting both data increase costs, which means that the benefits must be considered before the data collection. (Grierson 2014.)

6 Road measurement techniques and damage types

6.1 Road damage types

Pavement cracks and other damages in the roads affect the driving comfort as well as the driving safety. Surface and structure of the road deteriorate in a long run. Some of the reasons are, for example, age, climate and traffic. These may cause ruts and roughness to the road surface. It is important to obtain the damages and their magnitude and find out if further actions are needed. Structural damages are not always visible on the road surface, which is why those are harder to detect. Structural and road surface damages and cracking can be detected with different measurement techniques. (Ruotoistenmäki 2005, p. 16.) In addition to road damages, the shape of the road paintings, traffic signs and lights, street lightning, crash barriers and walls of the buildings are affecting safety in road environment (Pu et al. 2011, p. S28). Road damages, cross and longitudinal profiles and road geometry, such as, slopes are parameters which are studied in this thesis. All of these type of damages are possible to obtain with the laser scanner to a certain extent. Road structure can be divided into pavement structure, including the surface layer, and subgrade. Since laser pulses are not able to penetrate the ground surface, this thesis is focusing on the characteristics of the road, which can be obtained with the laser scanner.

6.1.1 Road surface damages and cracks

Roads are designed in such a way that they can endure static and cyclic stresses. Static stress is mostly caused by static traffic load and earth pressure, whereas moving traffic loads and thermal stress are reasons for cyclic stresses. Even if these factors are taken into account, sometimes it is not enough and cracks occur. (Doré & Zubeck 2009, p. 37.) Most of the road surface damages are consequence either from traffic load or from climate. Usually rutting is due to the traffic load, cracks next to edge are more likely because of consolidation of road and climate is causing the damages along the road centerline. In reality, it is not this straightforward to determine reason behind the damages and cracks. Typically, there are more than one reason causing the damages. Water increases the wearing of the road surface. Two main reasons are causing the surface damages; one is that the structure of the road does not correspond to the usage of road and another is that the planned life expectancy, has run out due to traffic and climate load. It is recommended to repair the damages before they expand. (Tiehallinto 2007, p. 38.)

The thermal cracking of the pavement is a consequence of variations in the weather conditions. Cracks, caused by thermal changes, are typically lateral, long and straight. Fatigue cracking is a sign of occasional tension that almost reaches the maximum strength of the material but does not exceed it. If the tension exceeds the maximum strength of the material, the pavement will crack but this is not the case in fatigue cracking. Cracking is a result of material fatigue. Poor pavement drainage assists cracking. Crack deterioration starts from a small deformation in pavement. Deformation can be due to thermal contraction or traffic load. Deterioration occurs in the long run and it is typically hard to stop when deterioration has initiated. Water accelerates the crack deterioration. Potholes are large cracks in the pavement surface and sometimes under it. Sometimes these can be rather deep and may cause safety hazards. Small cracks, water and traffic load are the three reasons causing the potholes. (Doré & Zubeck 2009, p. 58-59, 65, 69, 85-87.)

6.1.2 Longitudinal and cross profiles

Frost damages and subsiding are the main reasons causing the longitudinal damages, which are uncomfortable while driving a vehicle. The bad quality of the roadbed, traffic load during the frost season and heavy traffic might also cause longitudinal damages. (Ruotoistenmäki 2005, p. 16.) Longitudinal profiles provide information about the roughness, texture and humps of the road. The result of road roughness is usually presented using the international roughness index (IRI). This standard gives information about longitudinal roughness profile and driving comfort. Typically, the texture of asphalt is not homogeneous which increases the noise level. Cross profiles provide information especially from the rutting and height of the ridges. (Tiehallinto 2007, p. 5, 29, 24.) Cross profile damages are a larger problem in such roads where is a lot of traffic. Deformation of the subgrade, traffic load and deterioration of the road surface causes rutting to the wheel paths. Rutting can occur in the asphalt layer, in the structural layers or in the subgrade. (Doré & Zubeck 2009, p. 71.) Pavement deterioration increases during the frost season, in wintertime due to studded tires and in summer time due to heavy traffic (Ruotoistenmäki 2005, p. 16-17).

Maximum rut depths and water depths are example parameters, which are possible to obtain. Rut depths are measured for both traffic lanes so there are four rut depths in a two-lane road. These are determined by calculating average depth from a certain distance. Water rut depth is the depth in the area where there is a risk for ponding water. If the depths are deep, there is a greater change for hydroplaning, which effects safety and driving comfort. Besides these differing rut depths there are other interesting cross profile parameters such as slopes and crown of the road. Crown of the road is the maximum height between the left and right rut. Value can be either positive or negative. (Tiehallinto 2007, p. 28-29, 32, 34; Doré & Zubeck 2009, p. 71.) In Figure 9, is the classification for road condition, when defining variables are the rut depths. AVG is the average daily traffic and the color defines in which speed limit rutting is affecting driving comfort and road condition. Rutting will accelerate more in the future due to milder winters and increasing rainfalls. The road surface is wet and bare in early winter, which is nowadays a longer period than before. This will effect increasingly to the deterioration of the road markings. (Tiehallinto 2009, p. 42.)

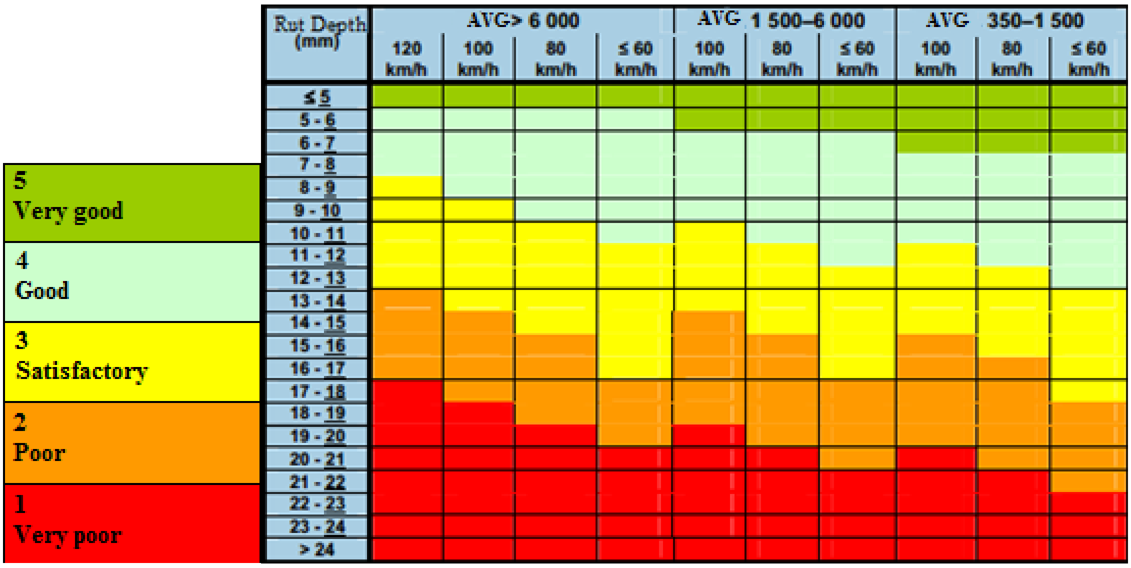

Figure 8: Classes for presenting condition of road depending on the rut depths and average daily traffic, modified (Tiehallinto 2005, p. 27).

Slopes are significant part of the drainage because it guides the water to trenches and rainwater outlets. On the straight roads, at least 3.0 % (1.7 degree) slopes are recommended and on curvatures it should be more. This depends also on the material of the road surface, for example, in graveled roads the slopes should be 5.0 %. Draining must be taken into account when planning a road. If longitudinal slopes are the main parameter in drainage, then the slopes should be tilted at least 1.0 %. Properly planned drainage prevents the formation of road damages and cracks because it keeps the water out of the road surface and structure. Road drainage can be divided into two parts; one is surface and another is the structural drainage. (Liikennevirasto 2013, p. 10, 20, 40.)

Fast lanes are planned in such a way that the cross fall is the same with the right lane, which means that there is no crown between the lanes. The crown of the road is usually placed on the left side of the fast lane. As it has already been said above, slopes are one main indicator when talking about the drainage. However together with road curves and steepness, safety aspects can be taken into account. Single-sided slopes should be between 3.0 -5.0 %, in road curves where the radius is from 85 to 160 meters and driving speed is less than 50 km/h. Maximum recommended slope is between 5.0 – 7.0 % depending on the classification of the road. If the slope is more than 7.0 %, it is usually due to the deformation of the road scene. (Tiehallinto 2007, p. 17, 37.)

6.2 Road measurement techniques

Road measurements are needed to keep on track of the changes in condition of roads and to show their present state (Tiehallinto 2007, p. 13). There are several road measuring methods of detecting road condition, such as, cracks and damages. The aim is to find the cause for the damage and the layer where the damage has occurred. The chosen measuring technique depends on the purpose and size of the area. Quality of the road measurements is highly dependent on the used technique, equipment and the measurement itself. Measurements should be reproducible but for example, the results, obtained by a visual inventory, vary much between the people who are doing the inventory. Every year large parts of the Finnish road network are surveyed in case of road damages, in total about

30 000 km. This is why it is important to have an efficient way of doing it. (Tiehallinto 2007, p. 14.)

6.2.1 3D Ground penetrating radar

3D Ground penetrating radars can detect structural layers and characteristics. The radar system has two antennas, one for emitting high frequency electromagnetic signals and one for receiving the transmitted signals. Time between the emitted and received beam can be used to measure the range, which can be detected from different layers. By measuring the range from antenna to different layers, it is possible to receive information about the thicknesses of the layers. (Ruotoistenmäki 2005, p. 41-42; Saarenketo 2010.)

Radars can be mounted on the back or in front of the vehicle. In Figure 8, is an example from the system mounted in front of a van. Depending on the radar type and driving speed, radars are installed from less than one centimeter to half a meter above to the road surface. Radars that are higher above the ground surface are better for detecting condition of pavement and radars closer to the road surface might be able to obtain characteristics under the pavement. Lower frequencies can reach deeper layers and even the roadbed. Longitudinal profiles can be detected with this technique. Interpretation of the data is time consuming and the accuracy depends on not only the quality of the instruments (radars) and amount of the data but in the addition professional skills of the interpreter. It is relatively inexpensive method to get an overview about the condition of the investigated area. Data from only 3D ground penetrating radar is usually not enough, which is why data from rotary drilling is also required. (Ruotoistenmäki 2005, p. 41-43.)

Figure 9: Road penetrating radar mounted on a van (Saarenketo 2006, p. 12).

6.2.2 The laser road surface tester

The laser road surface tester (RST) is able to obtain road damages, cross and longitudinal profiles. It contains various lasers that are mounted in a separate system either in front or the back of the vehicle. Lasers are installed in the face bar next to each other across the driving direction. More lasers are mounted on the part, where wheel paths are supposed to be, to detect rutting. This system includes typically also a camera, GPS and a data storage unit. (Tiehallinto 2007, p. 13.)

This method is able to record the measurements in real time but usually some post processing is still done. The position (X, Y and Z –coordinates) of the car can be determined with GPS system. The pulse sensor has been mounted in to the wheel of a vehicle to measure the travelled distance. (Tiehallinto 2007, p. 14.) Velocity of the vehicle depends on the speed limits and the weather conditions. The vehicle can contain about 17 lasers, depending on a system, and every laser collects 128 points in a 10 cm distance. These measurements are exploited for calculating the average value for every 10 centimeters. (Tiehallinto 2007, p. 14.)

6.2.3 Visual inventory

The visual inventory is focusing on the visible parts of the road such as pavement damages and cracks. A worker does the inventory from the slow velocity vehicle. The results of this technique depend much on the people who are doing the inventory and the weather conditions. If the road is wet, it is harder to recognize the cracks. Each worker may classify the cracks and damages to different categories. The visual inventory is a slow and time-consuming process. This technique is especially exposed to errors. This is why new techniques are more common nowadays. The visual inventory can be performed from the car or by walking. The results differ depending on the used method. The visual inventory by walking is extremely time consuming, which means that it is suitable only for small areas. If the inventory is done by using a moving vehicle, it is faster but the drawback is the erroneous of the method. The visual inventory can be carried out as well by using image and video data. When using image and video data, semi-automatic methods can be utilized. When using image data, it is important that weather and lightning conditions are good. (Ruotoistenmäki 2005, p. 32-33; Pu et al. 2011, p. S28.)

6.2.4 Laser scanning

Laser scanning has become more common in road applications. Scanning can be done either terrestrial, mobile or airborne. Terrestrial laser scanning is a time-consuming process in large areas because it is necessary to change the scanner's position between each scan. Stop-and-go laser scanning method may be useful in some cases when the surveyed area is not too large. Mobile laser scanning is rather new technique and it is able to collect dense 3D point cloud data faster than the terrestrial method. Cameras are usually mounted on a mobile platform to collect image data in addition to lidar data. It is suitable especially for road scenes. The point density of airborne laser scanning depends on the used parameters and platform. Aircrafts fly higher than helicopters so the point density is lower. Airborne laser scanning has been utilized, for example, to make surface models from road scenes. Many automatic methods, for recognizing, for example, pole-like objects or traffic signs from 3D point cloud, have been invented. The inventory of traffic signs, road paintings and other objects close to the road is possible to do from a laser scanned data. (Baltsavias, 1999b p. 168; Vosselman & Maas 2010, p. 36–38, 305; Pu et al. 2011, p. S28.)

7 Individual tree detection

Tree detection and forestry are widely investigated subjects in Nordic countries in the field of remote sensing. Especially individual tree detection has been a hot topic nowadays. Typically, growing stock areas are studied with area-based approach or individual tree detection methods (ITD). (Holopainen et al. 2011 p. 128, 130.) Individual tree detection, identification of tree species and investigating biomass are few examples from studied areas in the field of forestry. The land area of Finland is 86 % covered with the forest, which makes Finland the most forested country in Europe (Metla 2013). This means that it is important to find solutions that can be done automatically for forestry applications. Field investigations are time consuming and expensive especially in such large areas as Finland.

The main approach to individual tree detection is to find the local maximums of the canopy height models (CHM). In this method, it is assumed that the local maximum is the location of the tree even in reality it is not always so. Segmentation is used to separate the local maximums from each other. The final accuracy of the CHM depends on the pulse repetition rate. It is not possible to receive all the information from the 3D point clouds, which means that, for example, the diameter of the tree has to predict. (Holopainen et al. 2011 p. 130-131.) Forestry applications are one major section in utilizing laser scanning. It is still a large challenge to find all the forest characteristics automatically. (Moffiet et al. 2005, p. 291.) Full waveform laser scanners have improved the situation for extracting more information about, for example, tree trunks and ground surface beneath the trees (Yao et al. 2012, p. 368). Individual tree detection from the airborne laser scanned data has been researched much in recent years. Tree detection has been a studied topic in both area and individual level. Several algorithms have been developed to classify point cloud data and detect trees. The usage of these methods is still low due to detection errors. (Kaartinen et al. 2012, p. 952-953.)

Individual tree detection is challenging especially in areas where the trees are located close to each other and where trees are situated beneath the canopy. When trees are located close to each other, ITD algorithms usually recognize the group of trees as one tree. This means that the findings are typically underestimations. (Maltamo & Pitkänen 2003, p. 3.) According to Kaartinen et al. (2012, p. 953) article, the successfulness of the research methods may vary from 40% to 93%. The percent shows the number of correctly detected individual trees. Forest conditions are one factor affecting detection accuracy. The canopy height model is a widely used method. The local maxima can be determined from the model and these maxima are the locations of the trees. Low and medium level trees cannot be obtained from CHM if they are located next or under higher trees. It is possible to use 3D segmentation method for detecting individual trees and this method is able to obtain low and medium level trees as in Figure 10. It uses normalized cut segmentation to make a voxel representation from the point cloud. Coordinates of the laser beam, intensity values and pulse width are utilized in this technique. (Yao et al. 2012, p. 370.)

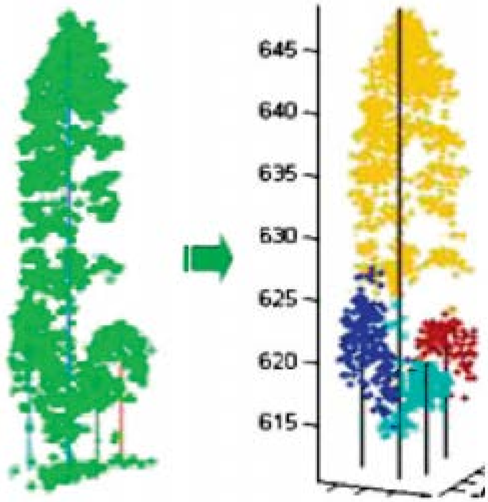

Figure 10: Principal of 3D segmentation (Yao et al. 2012, p. 370).

Laser scanning from helicopters is a convenient way to study curbside trees in urban areas. Public Works Department in the city of Helsinki is collecting information about trees in urban areas with the help of laser scanning. This information is utilized for the tree register of the city of Helsinki. Using both laser scanning and image data it is possible to obtain tree crowns, which have to be trimmed. (Mannila 2013; Raisio 2014.) In urban areas, there are specific challenges when detecting individual trees. Urban infrastructure gives challenges for tree detection. The characteristics of urban trees can be challenging for detection. Top of the tree might look like it has several tops and in a result, automatic detection can detect more than one trees. When old trees are replaced with new ones in tree rows, the new ones are hard to recognize with automatic methods. Some of the urban trees have been trimmed and it changes the appearance of a tree, which can affect the result of detection. (Tanhuanpää 2013.)

Several methods have been invented for identifying tree species. It is not an ambiguous task. For example, one method invented by Yao et al. (2012, p. 371) uses information about the outer and the internal tree structure, intensity values, characteristics of pulse width and reflections. Maximum likelihood classification is utilized to get the information about the species of individual trees. Raisio (2014) told at his interview that sometimes the tree species are cross breeding and tree specialists are needed to identify the species.

In Finland, some cities, especially the larger ones, have started to collect data about the trees and their features in urban areas. For that purpose, they have created a tree register where they can add information about the species, location and other needed information. The purpose of the tree register is on maintenance, plan and keeping track of the trees in the city area. (Tajakka 2013; Mannila 2013.) For example, Turku and Helsinki have started to create their own tree registers. In Figure 11, is the view from the tree register of Helsinki. Tree locations are marked with green shapes in the register. The aerial photograph is used in the background, which can be utilized for checking if the register matches with recent aerial photographs. Turku started to collect the data in 2007 and the project has reached its half way. Turku is one of the only cities in Finland, which has hired employees for creating the tree register. The deadline is set to 2018 and after that, the plan is to carry on to the maintenance of the data. That is one issue after the register is done how to keep the register up-to-date. (Tajakka 2013.)

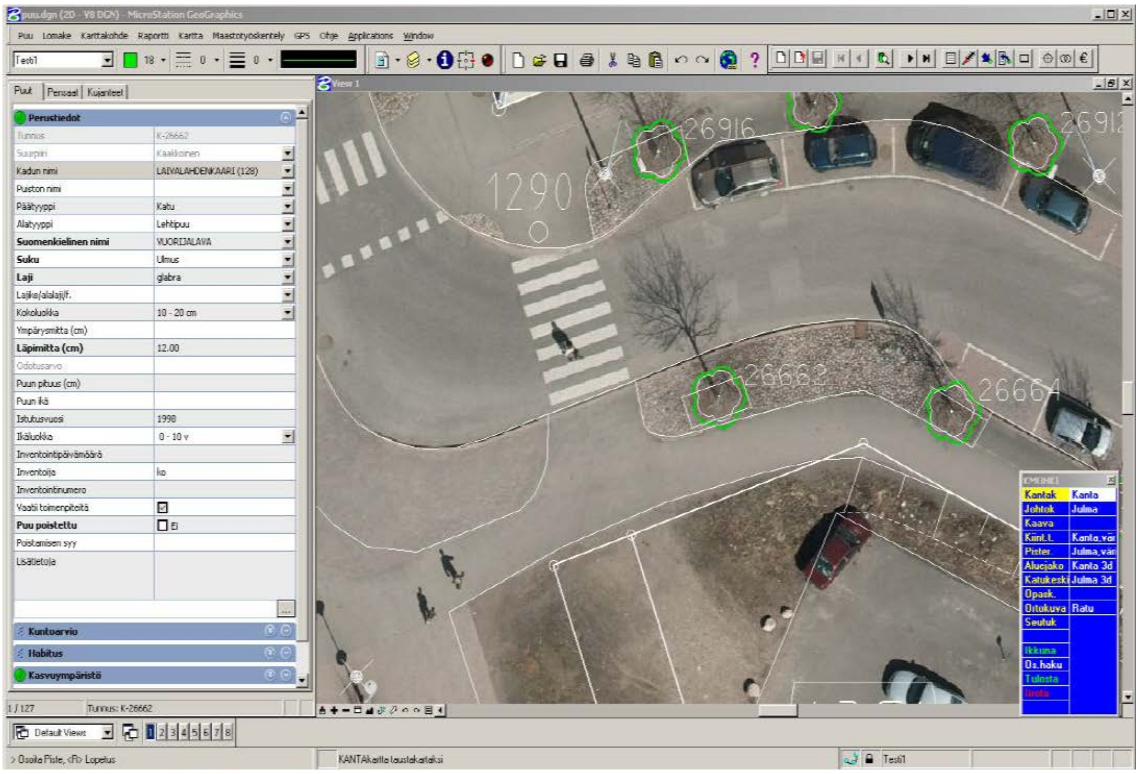

Figure 11: View from tree register of Helsinki (Ojamies 2012, p. 11).

The city of Helsinki uses much money for trees in urban areas. Price range for the individual tree can be from 2500 euro up to 10 000 euro. Tree register is a tool for individual trees maintenance, which is important to have since much money, has been invested in urban trees. (Mannila 2013.) Data collection for the tree register started several years ago in Helsinki and the oldest information in the current register is from 1999. The register includes about 20 000 curbside trees and several species. Data collection has been made in several methods with the result that location accuracy varies. Nowadays the data collection is more efficient and the aim is to achieve a ten-centimeter homogeneous accuracy for the whole register to increase usability. Most of the curbside trees are already in the register but collecting the information from the park areas is still at the early stage. The Department of Public Works has started to exploit laser scanning in the data collection with the co-operation of University of Helsinki, Department of Forest Sciences. Laser scanning provide information about the location and size of the canopy. In the city of Helsinki, arborists are collecting tree information data alongside their other work. (Raisio 2014; Tanhuanpää 2013.)

Ojamies (2012) has investigated the commissioning of tree register of Helsinki in his thesis. Ojamies assigns, that tree register is a convenient tool for individual tree maintenance. With the help of tree register, management plan for every individual tree can be made and time of doing the certain procedure can be determined. It is reasonable to determine time of a tree management by the region. If the maintenance work is divided a tree by tree regardless of the tree locations, the process is time-consuming. All the operations, that have been done, are marked to register. Updating the register requires site visits, to acquire information about the condition of the trees. Tree register can include the whole lifetime of a tree from planting to felling.

The majority of the cities that have started to collect information about trees in urban areas, do not have enough resources. Most of the work is carried out when there is not something critical to do. This means that the data collection is rather slow, expensive and it is exploited without any specific goals. Reaching the maintenance step, will take time if the survey is performed as fieldwork. It is important that the tree register is kept simple and there is no unnecessary information included. If there is less information in the register, the maintenance is easier and the data is more likely updated. (Tajakka 2013.) If individual trees are surveyed from urban areas, it is possible to use the register for change detection. There has to be data from the same area collected at different times. Change detection can be done from point cloud data when data sets are compared with each other. If data is available before and after storm, it is possible to detect the loss. Change detection can be done to monitor, for example, natural growth and forest management. This is not that common in urban areas. (Kankare et al. 2013, p. 66.)

One major sector in forest applications is biomass modeling. It has become studied area due to its ability to map and monitor the forest biomass. ALS has shown its potential for this purpose and that is why several methods have been invented. Obtaining point cloud data enables investigating the amount of possible bioenergy, biofuel and forest-bound carbon. There are not many results for investigating biomass at individual tree level. (Kankare et al. 2013, p. 66.) After creating a tree register model, it can be used in biomass modeling and visibility analysis. When the biomass is known, then it is possible to receive information about carbon storage. (Raisio 2014; Dobbs et al. 2011, p. 287–288.)

8 Material and methods

8.1 Detection of road damages

Blom Kartta Oy has a lot of helicopter-based airborne laser scanned data from various areas with different scanning parameters and varying point densities. The purpose of this empirical part is to find more use and value for the laser scanned data collected by helicopter. In addition, the benefits of BlomSTREET service in road environment monitoring are discussed. Empirical part of this thesis is divided in to two main parts, first part is focusing on the detection of road damages and drainage and the second one for detecting individual trees. There are three different data sets for investigating road damages. In the first case, ALS data is compared with data, which is collected with the mobile laser scanner. The second case includes two ALS datasets with different point densities and the results between these are compared. The purpose is to find out if the same damages are detected from both data sets and in which accuracy. In the thirds case, ALS data is used for finding road damages and 360 panoramic images in BlomSTREET for verifying these results. All the data used in this thesis have been collected and processed earlier.

Several road parameters can be computed from point cloud data with TerraScan software. It can be determined how frequently the road section parameters are presented, for example, every half a meter or every two meters. Maximum deviation is calculated from a line that is drawn from limiting points. The result can be positive or negative depending on the point's location. Different rut depths are possible to calculate; maximum rut depth, the water ruts depths and depths for the right and the left rut. Rut depths are calculated from a line that starts from the middle of lane to the right or left edge of the road depending on, which rut is in question. Final depth is the largest deviation from a point to the line. Maximum rut depth is the largest rut depth on line. Water rut depths are computed a similar way but the depth is the longest distance from a point to water surface. (Soininen 2014, p. 170-171, 300-301.)

8.1.1 Case Jakomäki

Jakomäki is located in Southern Finland and in the Northeastern part of the capital area. Jakomäki case consists of two datasets, one dataset is collected with the mobile laser scanner and another is collected with the low altitude airborne laser scanner. Investigated area is a two-lane highway from which another lane is the passing lane. Both datasets cover the same area and are collected in the year 2013. In MLS data, the point density is higher than in ALS data. The results from lower altitude data are compared with the results of higher point density MLS data. The main goal was to investigate what kind of road parameters can be found from helicopter-based data that is originally collected for some other reason, such as, to make a surface model. TerraScan's tools were used to receive information about road geometry, cross and longitudinal profiles, slopes and rutting.

First dataset is collected by the mobile laser scanning system. Scanners were mounted on a car that was driving on a highway. Point density varies much in the surveyed area due to velocity changes and the location of the platform. A car was driving on the right lane, which is why the point density is higher on that lane. Variation is from 1000 points/m^2 to 1800 points/m^2 and on the passing lane from 200 points/m^2 to 500 points/m^2. Point cloud data includes some gaps, on the road surface, which are mostly due to other traffic.

These gaps are important to take into account so that they do not distort the results. Other dataset includes helicopter-based point cloud data that has lower point density when compared to MLS data. The point density varies much in surveyed area due to overlapping flight lines and gaps. Variation is between 40-100 points/m^2. In this data set, there are some gaps because of the other vehicles. The goal was to make needed investigations in MicroStation V8i using Terrasolid's TerraScan software. Road parameters were calculated every meter using macros and the results were as a text file that could be imported back to MicroStation via TerraScan. The results can be compared visually in MicroStation and numerically using Excel. Computed slopes are giving an idea about the drainage but water flow can be displayed more clearly with TerraModeler. The locations where water flow stops and accumulates are visually presented.

In Table 1, the main information about the survey flights is presented. All the data are collected within two years and TopEye systems have been used for data collection. Data have been collected helicopter-based and the altitude varies from 350 meters to 500 meters. It can be seen from the Table 1 that the point density in MLS data is multiple compared with the helicopter-based data. Even the lower point density on the passing lane is twice as high as in low altitude point cloud. In Jakomäki case, the point density from the airborne laser scanned data is in some parts of the road scene lower than in Hyvinkää and Rauma (higher point density) data. The point density varies due to over lapping flight lines and occlusion.

Table 1: Parameters of laser scanned data

	System	**Flying height [m]**	**Average point density (points/m^2)**	**Data collected (year)**
Hyvinkää	TopEye S/N 443	350	94	2014
Jakomäki (ALS)	TopEye S/N 533	450	40-90	2013
Jakomäki (MLS)		-	Right lane: 1000-1800 Passing lane: 200-500	2013
Rauma (lower point density)	TopEye S/N 533	500	26	2013
Rauma (higher point density)	TopEye S/N 533	400	91	2013

8.1.2 Case Rauma

Rauma is located on the West coast of Finland. Blom Kartta Oy has the laser scanned the old part of the town twice with different parameters and point densities. The other dataset is collected from larger area with a lower point density and another includes only the old part of the city with higher point density. The data was originally collected to produce data for the digital elevation model (DEM). The time of the aerial survey was in May 2013 and it was completed within two days. Eteläkatu is one of the largest and most active streets in the surveyed area, which is why it was selected. Investigations were made for a road section about 710 meters long. The most significant flight information can be found from Table 1. There is 100 meter altitude difference between the two flights. Another flight's altitude from ground was 400 meter and another's 500 meter. The average point density for the higher density data is 91 points per square meter and for the lower density data; there are 26 points per square meter. In both datasets, the point density varies depending on overlapping flight lines and gaps.

Virtual reference stations were used for processing the GPS data. To compute a 3D point cloud, the data sets including GPS, IMU and laser measurement were integrated using TopEye's TEPP software. Relative accuracy between individual flight lines was determined in the four-step process. First step was to classify ground points from the separate flight lines and then the system boresight calibration was done by determining the pitch and heading misalignments. Blom's TASQ (TopEye Area Statistics and Quality) software calculated the statistics for the alignment between the flight lines. Finally, the individual corrections were found with TerraMatch, for each flight line in X, Y, Z, roll and mirror scale. For higher point density data, the total RMS error (dZ) was 0,033m. For lower point density data, the total RMS error was 0,057m before matching and after it was 0,048. The main goal is to compare the data and determine the differences in road parameters. The same methods for finding road damages are exploited as in the Jakomäki case.

8.1.3 Case Hyvinkää

Third dataset is from Southern Finland, City of Hyvinkää. This data includes laser scanned data collected with helicopter and 360 degree georeferenced panoramic images from BlomSTREET service. BlomSTREET images are used as a reference data to control correctness of the results computed from lidar data. Both data sets are collected in 2014. Original purpose for the data was to make an elevation model. Investigated part of the road is about 100 meters long. At first, the slopes are calculated using TerraScan tools. The spots where slopes deviate suddenly can be marked and exported to BlomSTREET. It is possible to control and check, if the results match with the ones computed with TerraScan. Slopes are calculated on both longitudinal and perpendicular to the driving direction. In addition, slopes are exploited to find potholes and other large road damages. If the slopes are set close enough to each other, sudden changes can be detected in both directions.

Lidar data fully covers the area and the point density is smooth with exceptions for watersheds. Virtual reference stations were used in the GPS processing. GPS, IMU and lidar measurements were integrated by using TopEye's TEPP software with a result of 3D point cloud. Same road parameters are calculated and presented as in case Jakomäki and Rauma. The changes detected in slope arrows can be drawn to MicroStation to own level that can be imported to BlomSREET for further control. When drainage is displayed and drawn to its own level in MicroStation it can be exported as it is to BlomSTREET. It is possible to see the real locations for water gathering points and if there is a rainwater outlet or if the location has problems with drainage.

8.2 Individual tree detection in Korppoo

One data set was available for studying individual tree detection. The last data set includes lidar data and surveyed tree location points. The aim is to investigate how well TerraScan's automatic tool for individual tree detection is working. Terrasolid's software TerraScan is utilized to detect individual trees from the point cloud data. Data has been collected from Korppoo and Parainen municipality area in the South-West of Finland. The locations of 17 trees were surveyed to get a reference data for automatic individual tree detection. In the Table 2, below, are listed the flying height, laser scanner system and average point density of the data.

Table 2: Laser scanning parameters for Korppoo area

	Flying height (m)	System	Average point density	Data collected (year)
Korppoo-Parainen	400	TopEye S/N 534	28 points/m2	2014

The purpose of this study is to find out, if it is possible to detect individual trees and in which accuracy. The height parameter is also investigated. First, the height of a tree is manually measured from the point cloud data. Then the results are compared with TerraScan's automatic height determination. Focus is on planted trees that are located, for example, next to streets in urban areas.

8.3 Used softwares

In this thesis, three main software and products were utilized. Two of them are TerraSolid's software, which work in MicroStation. The first, is TerraScan that was the most used software in this thesis. The second one is TerraModeler that was utilized on the surface modeling and testing the drainage of roads. BlomSTREET is the third main product that was exploited. The results of TerraSolid's software and BlomSTREET were merged to get the best possible result. The results from TerraModeler and TerraScan can be exported to BlomSTREET and vice versa.

8.3.1 TerraScan

TerraScan is a software for handling and processing lidar data. It works on top of MicroStation. It enables to classify and analyze point cloud data, manage trajectories, and make coordinate transformations. Point clouds can be colored, for example, by intensity, echo, class and flight line and it can be utilized in the data analyze. For managing large lidar point clouds, it is possible to create projects and import points into a project. TerraScan provides tools for a wide range of different applications such as power lines, the road and the railroad and 3D building models. Some of the road tools require high point density, which means that those are developed for mobile laser scanning data. Otherwise, the functions are not mainly dependent on the acquisition method. (Soininen 2014.)

8.3.2 TerraModeler

TerraModeler is developed for creating terrain models from data collected with different methods. As well as TerraScan it is developed to work on top of MicroStation. The software provides several tools for general functions, drawing elements and profiles, creating and editing surfaces models. Surface models are possible to triangulate from different data sources. The software is capable to handle data from multiple sources and creates a surface model from those. TerraModeler has a function to generate displays such as contours, grid, slopes and triangles. (Soininen 2013.)

8.3.3 BlomSTREET

BlomSTREET is a cloud-based service that includes the set of street view 360-degree panoramic images. The panoramic image is merged from images that are oriented and taken with several cameras. The resulting image can be produced without any parallax. In Figure 12, is presented a basic view from BlomSTREET. High-resolution images are taken every five meters to fully cover the needed areas. During the data acquisition, the weather conditions are taken into account to provide full visibility. A dual camera, GPS, IMU, real-time firmware and distance measurement interface are mounted on a car. For driver and the data collector there is a control and user interface placed on a vehicle. Due to the precise position accuracy and good geometry of the images, it is possible to use BlomSTREET for measuring and inventorying distances, traffic signs and road damages. It is possible to upload custom layers in WFS, WMS, shape file and SLD file formats. For example, plot boundaries and other information is possible to upload to BlomSTREET. All the measurements done in BlomSTREET can be exported in standard file formats. (Blom Kartta Oy 2014.)

Figure 12: Planted tree row in Helsinki (screenshot from BlomSTREET).

9 Results

9.1 Longitudinal and cross profiles

When helicopter-based laser scanning is performed, there may be gaps in the data due to watersheds, vehicles or other objects between the road surface and the helicopter. If there are gaps, road parameters will not be able to calculate accurately and road damages remain undetected from those locations. With TerraScan, it is possible to compute road section parameters such as rut depths, slopes, cross roughness and maximum deviation. TerraScan's tools for road parameters are mainly intended to higher point density point cloud data. The best results can be achieved when road section parameters are calculated from MLS data. Low altitude airborne point cloud data is not as dense as the mobile laser scanned data and therefore it is not reasonable to investigate all road parameters that can be computed with TerraScan. For example, the cross roughness of the road pavement is not accurate when it is computed from helicopter-based data. Point density is not enough to the present average cross roughness of the road surface because in these cases the cross roughness presents the deviation of the laser points. Large deviation values might be a sign from a pothole.

When the helicopter laser scanned data is used to detect the road section parameters and slope arrows, it is clear that with low-density point cloud data, the identification of road damage types is not yet possible. In some cases, it is possible to identify the longitudinal or cross profile damages but without images, these are difficult to determine more precisely. Slopes are one option for detecting longitudinal profiles and cross profiles. If the perpendicular slope arrows are computed and set dense enough, sudden changes in longitudinal profiles can be detected. Changes in the cross profile are possible to determine with longitudinal slope arrows. However if some of the road section parameter values are extremely high or low, these locations should be examined more closely from the point cloud data, for example, using vertical cross sections. The high water rut –values can be a sign of potholes. Verification has to be done manually, which is time-consuming. If there is image data available, it can be used to recognize damages and to control the results. From MLS data, more accurate results and conclusions can be obtained. By reducing the amount of data, it enables the software to work faster, which is why area sizes have been reduced for only significant areas and only for lanes and their surroundings.

Jakomäki

For Jakomäki, the investigated part of the highway is rather new and is in good condition. Values of road section parameters were small and there were no sudden changes in longitudinal or cross profiles. Drainage is working properly in the area and there is no water gathering on the traffic lanes. Below, there are two images, Figure 13 is presenting rut depths that are computed from MLS data and Figure 14 is presenting rut depths that are calculated from helicopter-based lidar data. Point clouds are colored by slopes, which displays, for example, rutting. Colored 3D point clouds are used in the background of both figures to see the differences more clearly. Locations of the ruts are marked with yellow dots and depths are presented in millimeters. From Figure 13 it can be seen that on the right lane, rut depths are smoothly following the wheel tracks but on the passing lane, X-Y -locations of rut depths vary slightly more. This is due to point density difference between the two lanes; on the right lane, the point density is about $700^{p}/_{m^2}$ higher than on the left lane and this can be seen clearly from Figure 13. The results are more reliable and accurate if the point density is high. The average distance between the ruts on both right and left side is about 1.6 meters, which is about the same length as the distance between the tires of a basic sedan. (Mercedes Benz 2014) This fact supports that the obtained results are located on the actual wheel tracks. On the passing lane, the values are generally smaller and this is because it is the passing lane and its use is not as high as compared with the right lane. Even if not all rut locations are on the same line, the rut lines can be clearly seen. For helicopter-based data, the average distance between right and left rut is less, about 1.2 meters.

Figures 13 and 14 are captured from the same area. The locations of the right rut depths in Figure 14 are closer to centerline than in Figure 13 and they are also smaller. If the rut depths are just a few millimeters, they are not affecting the driving comfort. According to the Finnish transport agency (Tiehallinto 2005), the condition of a road is classified as good or very good if the velocity of the car is 120km/h and rut depth is smaller than nine millimeters, which is displayed in Figure 9. If the rut depth is between 13-17 millimeters, with the same velocity condition of the road, it is classified as poor. Average rut depths for this section of the road were for the right lane for MLS lidar data around one centimeter and for helicopter-based lidar data from six to seven millimeters. According to Figure 9, this road section's condition would be classified as good with low altitude airborne data and as satisfactory with MLS data. Average, minimum and maximum values for both lanes calculated with both MLS and helicopter-based datasets can be found in attachment 1.

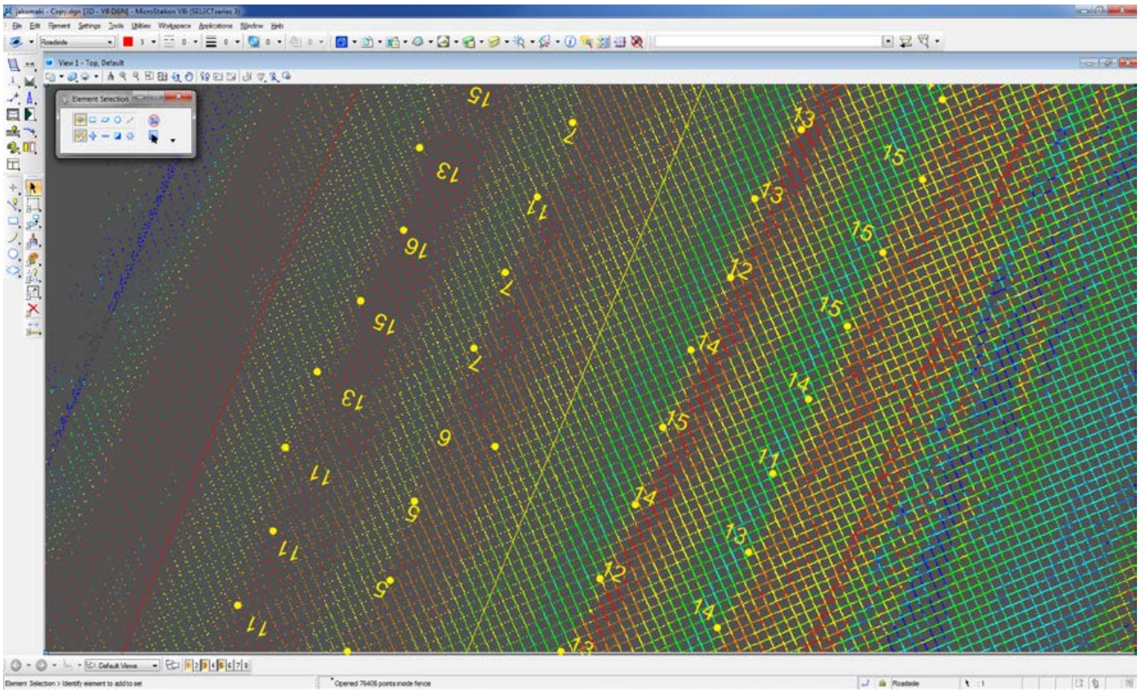

Figure 13: Rut depths computed from MLS data.

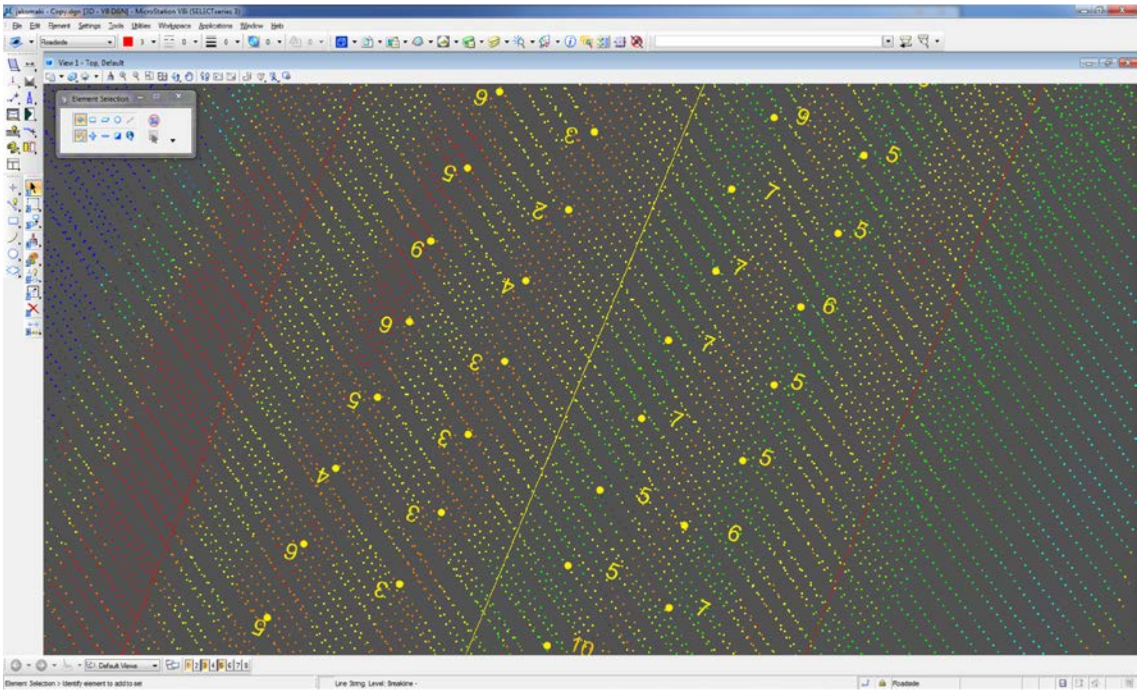

Figure 14: Rut depths computed from ALS data.

The obtained values are generally larger in MLS data than in ALS data. The average differences for the right lanes are 0.0049 meters and 0.0064 meters and for the left lanes 0.0038 meters and 0.0053 meters. These values are quite close together but not all values are actually comparable because the locations of the ruts vary much as it can be seen from the Figures 13 and 14 above. When the point density is higher, it is possible to determine the accurate road surface and the changes can be obtained more precisely. In low point density data, the road surface is not as unambiguous as in higher point density data, which is why it is more prone to errors.

With slope arrows, it is possible to investigate the road drainage and sudden changes. Drainage is checked more closely in Chapter 8.2. In these datasets, the slope arrows are running smoothly and no sudden changes were detected. Perpendicular slope arrows are computed for every half-meter and longitudinal slope arrows for every meter. As it can be seen from Figure 15, values of, adjacent arrows are not changing significantly. The maximum difference for adjacent arrows in MLS data is 0.1 degrees for both lanes; this means that the change is six millimeters. For helicopter-based data, the differences are for the right lane 1.2 degrees and for the left lane 0.3 degrees. On the right lane there is a 30 meters long section of the road where the average difference is 1.1 degrees and the maximum difference is 2.0 degrees between the two datasets. When checking the helicopter-based lidar data more closely, it turned out that there was a truck driving on the road, blocking the direct view to the surface of the road for that 30-meter section. This means that there are fewer points on the road surface and it is causing some error when calculating the slope arrows. The average difference between the ALS and MLS data was only 0.08 degrees.

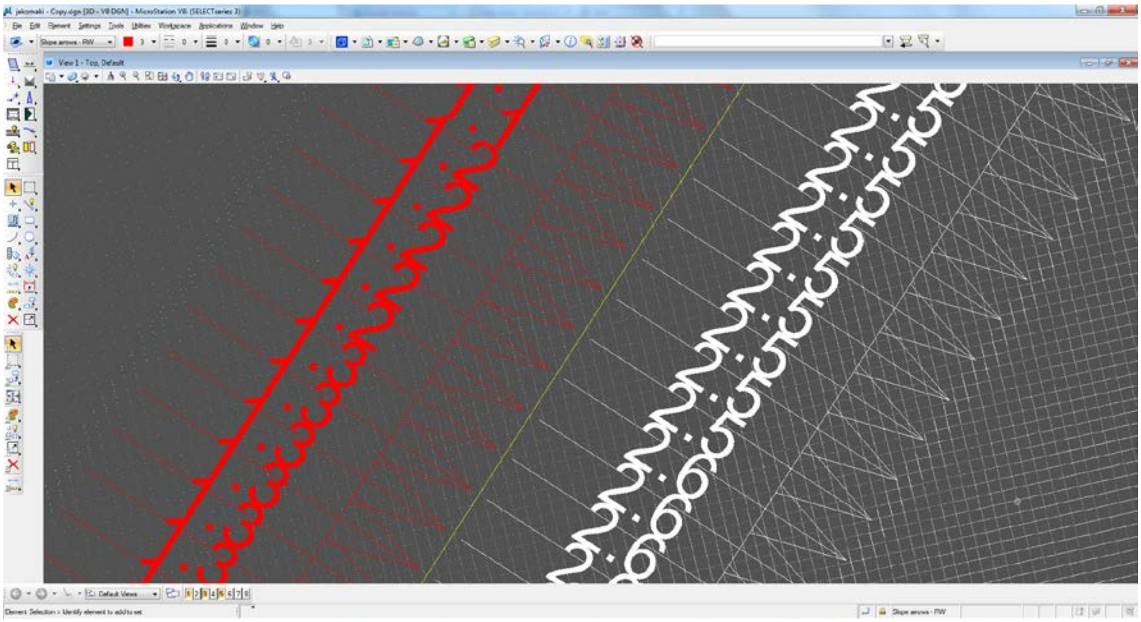

Figure 15: Slope arrows (degrees) calculated from helicopter-based data.

It is possible to investigate road humps and sudden changes in road surface with the help of adjacent slope arrows. The average difference was 0.05 degrees for the right lane and for the passing lane the value was 0.03 degrees when results were calculated from ALS data. The equivalent values were 0.02 degrees for both right and passing lanes when computed from MLS point cloud data. Maximum deviations for adjacent slope arrows were 0.11 degrees on the right lane and on the passing lane 0.13 degrees when the mobile laser scanned data was used. Corresponding values from ALS data were 1.64 degrees and 0.34 degrees. In low altitude data airborne, the higher right lane value is due to the truck that was previously mentioned. Values for the passing lane were higher but not significantly. The differences with two datasets are not varying significantly. With helicopter-based data, it is possible to get similar results as from the mobile laser scanned data especially when comparing slope arrows. In addition, these values are presented in attachment 1.

Rauma

Especially in the Rauma case, the maximum deviation varies greatly in both higher and lower point density data sets. Values in higher point density data are between -0.083 and 0.072 meters. For lower point density data, the corresponding values are varying between -0.109 and 0.069 meters. These highest and lowest values are large and could be a sign of error points. If only point cloud data is utilized, it may be difficult to confirm if there is some kind of damage. Images are useful for assuring the results. Rut depths are not as smooth and accurate as in MLS data when these are computed from helicopter-based lidar data as it can be seen from the Figures 16 and 17, which are taken from the same location. Locations of ruts vary much from the wheel paths. In higher point density data, the average distance between ruts is for the right lane 1.1 meters and 1.2 meters for the left lane. In lower point density data, the equivalent values are 0.4 meters and 0.5 meters, which is less than the distance between the tires. This shows that it is not possible to obtain accurate positions of rut depths with these point densities.

In lower point density data, the X-Y -locations of rut depths are obtained really close to the line where they have been calculated, which can be seen from Figure 17. The locations of rut depths are detected smoothly but to wrong places. The point density in this data is rather low and probably too low for TerraScan's road section parameter –tools that are meant mainly for MLS data. Even when the values of the parameters were changed, the results did not improve. Another problem, when using low-density data, is that TerraScan's tool is not able to determine road section parameters and slopes for the whole data set. This causes large gaps to the results in areas where the point density is low.

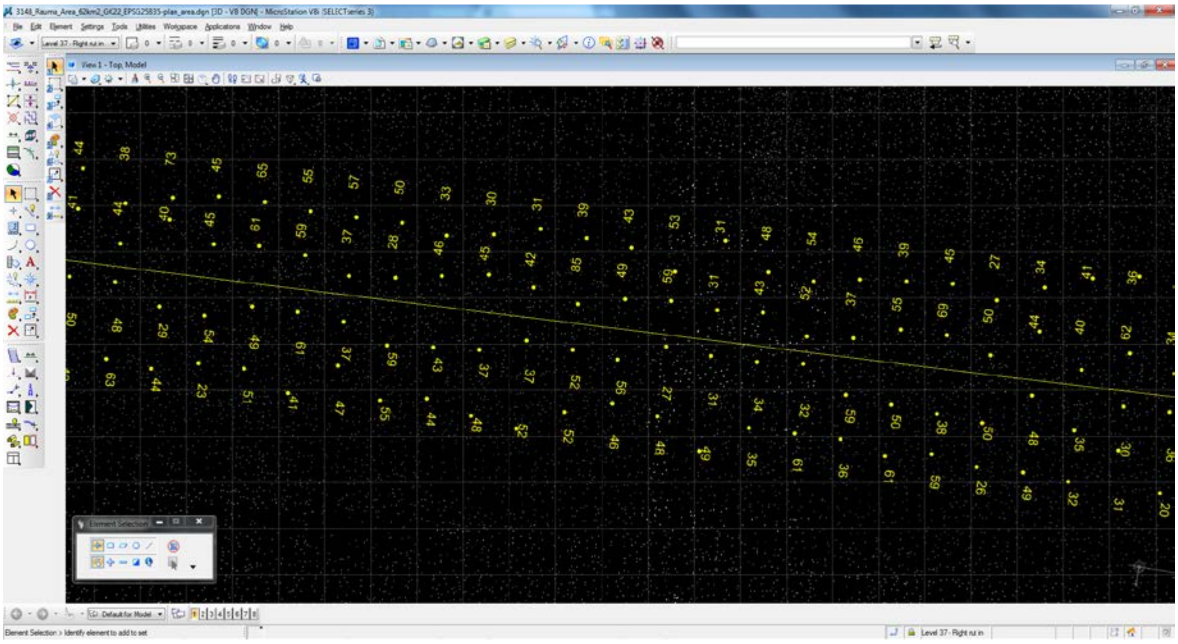

Figure 16: Higher point density data from Rauma.

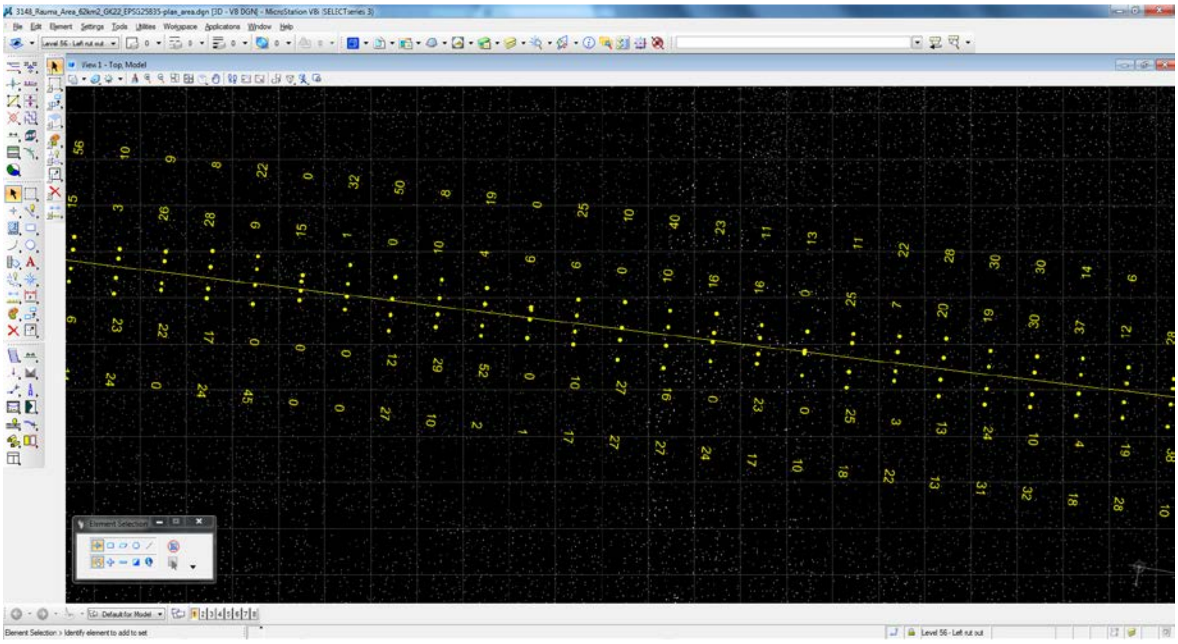

Figure 17: Lower point density data from Rauma.

Perpendicular slope arrows were obtained every-half meters. On the left side of Figure 18 the slope angles are quite close to 3.0 degrees then it suddenly increases to 4.0 degrees and then decreases back to 3.0 degrees and then again from 3.2 degrees to 2.3 degrees. Large changes, between adjacent slope arrows, can be a sign from road damages and these areas should be checked more closely, for example, from images if there are images available. These kind of damages will affect the driving comfort and makes driving rugged. Average differences between adjacent slope arrows were 0.18 degrees for right lane and 0.17 degrees for the left lane in the higher point density data. Corresponding values for lower point density data were for 0.27 degrees for both lanes. Values in lower density data are slightly larger because the slope arrows are deviating more when there are fewer points per square meter.

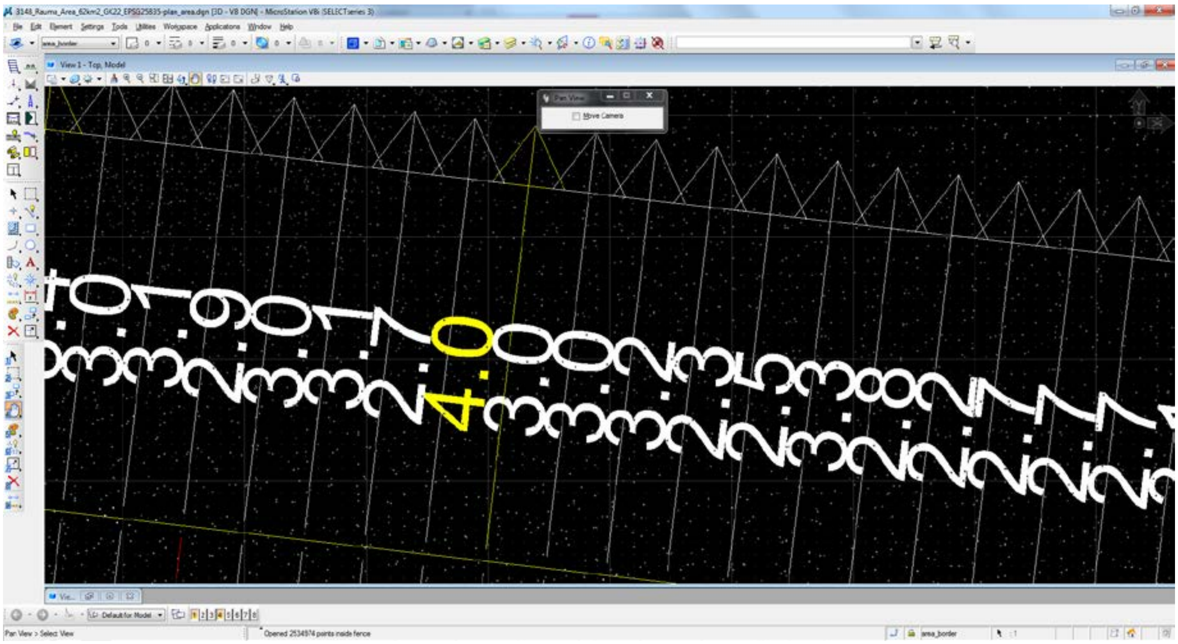

Figure 18: Slopes (degrees) computed from higher point density data (Rauma).

Maximum differences between two adjacent slope arrows are higher than in airborne and the mobile laser scanned data in the Jakomäki case. There are two reasons for that, one is that the road is in a worse shape and the other is that point density is lower. For higher point density data in Rauma case, the maximum differences are 1.37 degrees and 1.32 degrees while for another dataset equivalent values are 2.34 degrees and 1.58 degrees. The average difference between higher and lower point density data for the right and left lanes was 0.25 degrees. The results are similar to each other, which means that slope arrows are possible to compute accurately even though the density of the point cloud data is rather low. All the calculated values for Rauma datasets can be found in attachment 1. For lower point density data, longitudinal slope arrows could not be calculated. Slope arrows for higher point density data were visually displayed in MicroStation and the variation between sequential was large. Both 3D point clouds were colored by a slope. Coloring clearly shows that the highest point is between the lanes and some rutting was also detected.

Hyvinkää

In the Hyvinkää case, there was a similar problem as in Rauma's lower point density data when calculating the rut depths. The locations of ruts were obtained close to the break line that was used to compute the rut depth values. Average distances between the ruts were for the right lane only 0.15 meters and for the left lane 0.14 meters, which is way less than the tire spacing. Rut depths were about 0.04 meters in both lanes and maximum rut depths were about 0.05 meters. Average rut depths for the right lane are less than two centimeters and for the left lane about two centimeters. With these results, the condition of this section of the road would be classified as poor according to Figure 9. In Figure 19, slopes color the point cloud data and rutting can be clearly obtained. The red cross is presenting the same spot in MicroStation and in BlomSTREET. Ruts can be seen from images since the color of asphalt is darker on the wheel paths.

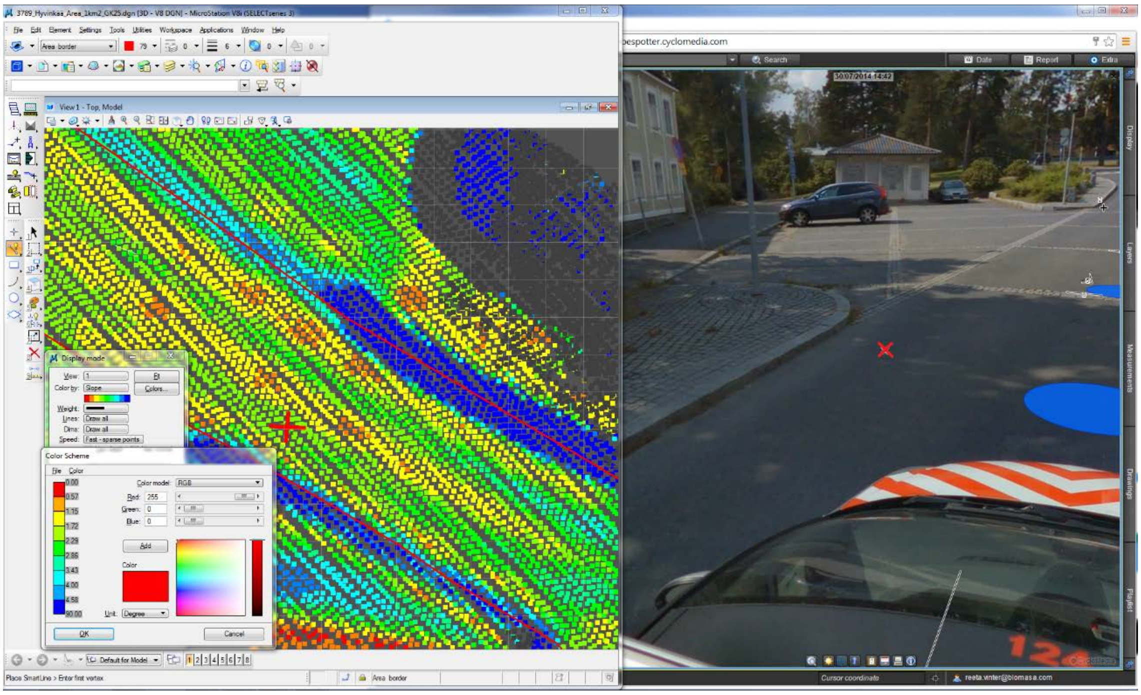

Figure 19: Rutting displayed in MicroStation (left) and BlomSTREET.

Panoramic images in BlomSTREET were used for controlling the results from lidar data. It is not possible to import text data to BlomSTREET and therefore all locations where some sudden changes in slope arrows or high values in road section parameters were detected, were marked into a new level in MicroStation. Slope arrows have been utilized for detecting changes in the road surface. In Figure 20, the percentage varies between adjacent and sequential slope arrows calculated every 1.2 meters. For example, 1.5 degrees longitudinal slope arrow, marked with the red color, has 1.9 degrees difference from its adjacent slope arrow, which is 3.3% difference and according to Liikennevirasto (2013, p. 40) over 1.0% values for longitudinal slopes are enough. The same slope arrow has 1.4 degrees and 1.0 degrees differences from its sequential slope arrows. TerraScan was not able to compute slope arrows for the whole area therefore some gaps remained, for example, in the upper right corner of Figure 20. The largest deviation between sequential slope arrows was 7.47 degrees. When intensity values and images in BlomSTREET were utilized, it was seen that there was a raised pedestrian crossing.

Figure 20: Longitudinal slope arrows (degrees) calculated from helicopter-based lidar data.

One longitudinal pothole was found from the location where the maximum deviation value was the highest for the left lane. There were three road damages located close to each other. In this part the maximum deviation and rut –values were about four centimeters, which was generally higher than elsewhere in the area. Average maximum deviation for the whole area was around zero and average value for maximum rut depths were from two to two and a half centimeters. Similar road damages were found with the help of longitudinal slope arrows. If the deviation was large, locations would be controlled also from BlomSTREET. The largest differences were 2.2 degrees and 2.7 degrees between sequential arrows and from BlomSTREET's panoramic images, it was possible to confirm the damages. There was some deviation in other areas and the average deviation for longitudinal slope arrows was 0.86 degrees. This means that there are some humps on the road. Perpendicular slope arrows were calculated for every half a meter. For the right lane, the maximum difference was 0.71 degrees and average difference 0.17 degrees. Corresponding values for the left lane were 1.21 degrees and 0.21 degrees. Average and maximum values for Hyvinkää dataset can be found in attachment 1.

From these five datasets it is possible to obtain that when the point density is getting lower the rut locations are detected closer to road center line or edge lines depending on which has been used for computing the road section parameters. Even though it is not possible to receive accurate information about rut depths, values can still be utilized for detecting other types of road damages. For example, maximum rut depths and maximum deviation can allocate location for larger damages. After receiving the results from the analysis of the data, it is important to check more closely especially the areas that differ from each other. If images are available, it is a good way to control the results.

9.2 Drainage

One part of the thesis was to investigate the flow of drainage water in the test areas. Terrasolid's software TerraModeler was used to create a ground surface model utilizing 3D point clouds. The surface models were utilized to compute and display the water flow. The arrows are showing the direction of the flow. Water will accumulate in areas that are marked with red squares. Red squares have a value that is the size of runoff area in square meters. Runoff area includes all the grids from where the water drop travels until it reaches the lowest point. Grid size is determined as $1m^2$ and the level of detail can be modified depending on how detailed presentation is needed. Lower levels of details show only the major water streams. Water flow is important to lead off traffic lanes to avoid, for example, hydroplaning and avoid the deterioration of the road surface and structure. In Figure 21, the drainage is presented from Hyvinkää data. The pink area is showing the run off area of a water flow for a red square on the lower right corner. Size of this run off area is $387m^2$. This means that in heavy rain, water will gather next to raised pedestrian crossing.

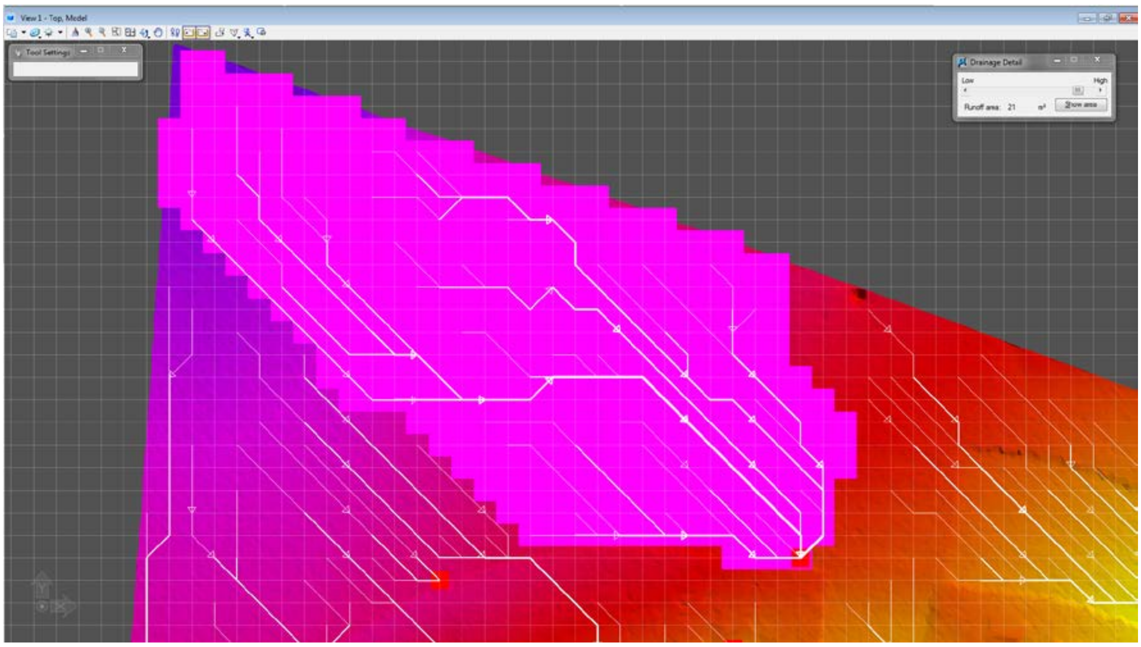

Figure 21: Runoff area of pour point in MiroStation V8i.

After displaying the drainage with TerraModeler in MicroStation, it was transformed in to a Shape file to add as a layer in BlomSTREET. In Figures 22 and 23 the imported drainage layer is displayed both in the map and in the panoramic views, the area in Figure 22 is the same as in Figure 21. Light blue dots are the locations where images have been taken and those are approximately located in every five meters. Red squares are the spots for pour points, the places where water flow will stop. If there is rainwater outlet the water will flow through, otherwise it will pool in these spots.

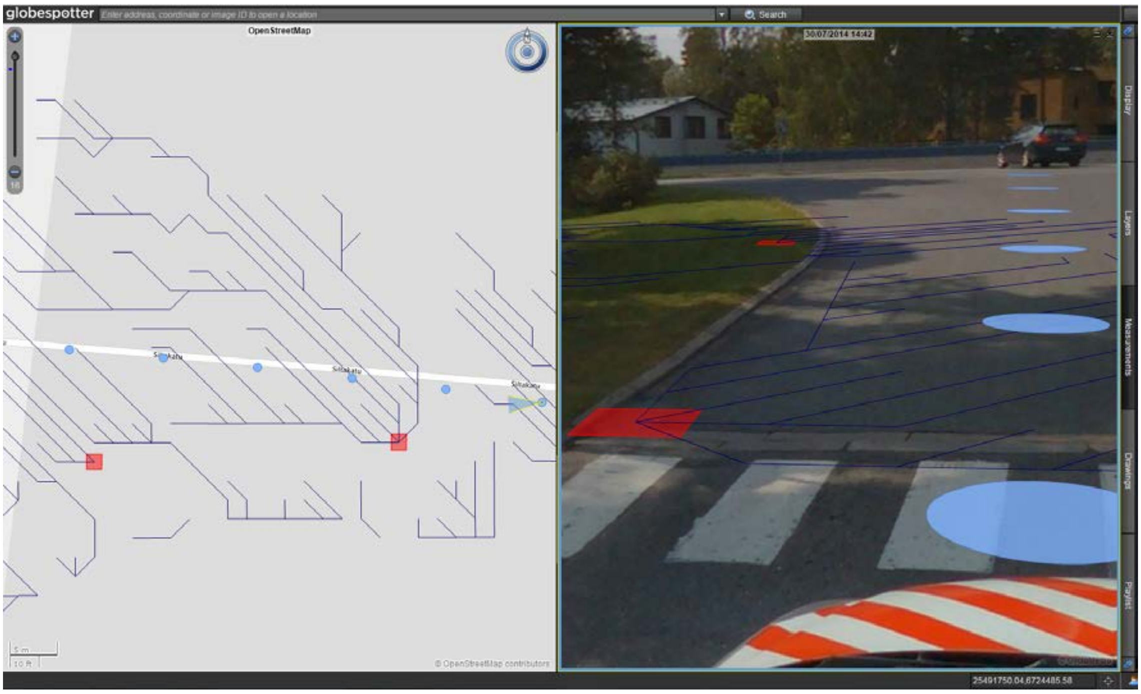

Figure 22: Drainage displayed in BlomSTREET.

The difference between Figures 22 and 23 is that in Figure 22, drainage is not functional since the pour point is located next to heightened pedestrian crossing without a rainwater outlet. Therefore, it will gather a large puddle due to large run off area. Instead, in Figure 23, drainage is working because there is a rainwater outlet placed on the same location as the pour point is. Size of the runoff area for lower pour point is $321\mathrm{m}^2$.

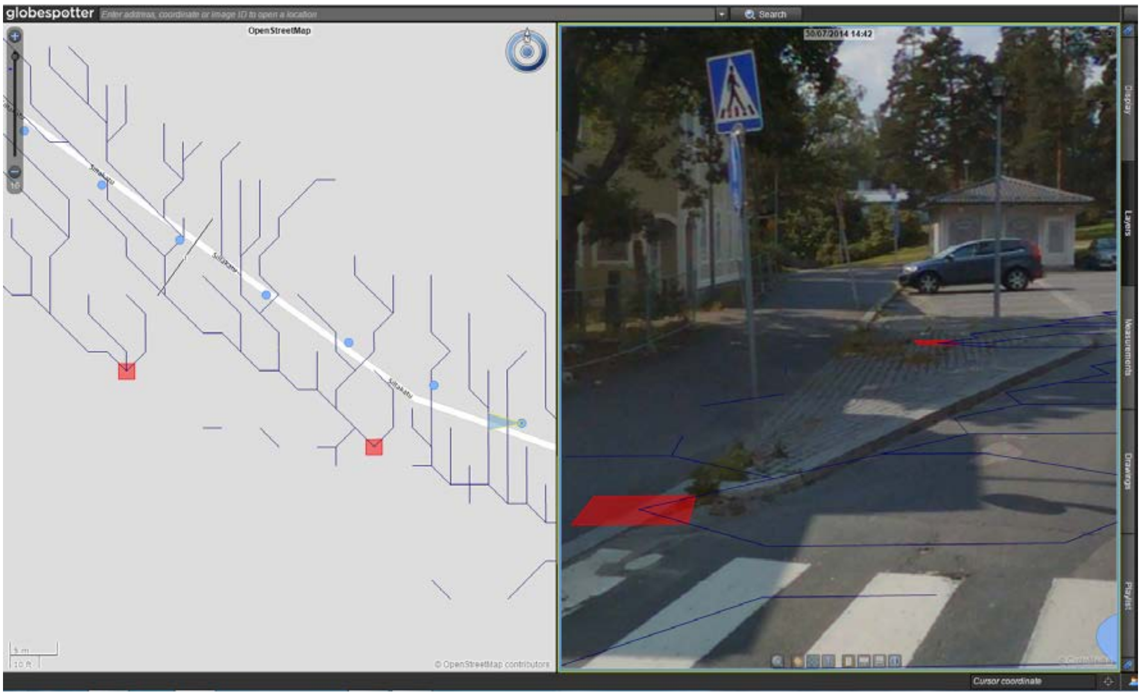

Figure 23: Drainage displayed in BlomSTREET.

In Jakomäki, the ground surface model is limited to the roadside ditch. The red squares, located in the trench bottom close to the edge of the area, were not examined more closely since water would flow further. Most importantly, if water is not gathered to traffic lanes, it is not harmful for road surface and structure or traffic safety. The results for drainage are similar to both MLS and ALS data. The edge of the road has been marked with red color and the centerline with yellow in Figure 24. In general, there were a few pour points (red squares) located in traffic lanes. It means that the highway is in a good condition and water is led off from traffic lanes. Especially in highways, it is important since the velocity of the traffic is higher, which increases the risk for hydroplaning. Only in one part of the investigated road, there were problems in road drainage, which can be seen in Figure 24. It is the part were the highest point (break line) of the road changes the place from the left edge of the road to the right edge of the road. The highest point of the road changes due to bend. Four of the red marked runoff areas are located on the traffic lane, which are the same order of magnitude. The sums of the run off areas for these four pour points in ALS and in MLS datasets were really close to each other, the difference was only $2m^2$. For low altitude airborne data, the sum of the run off areas was $45m^2$ and for the mobile laser scanned data, it was less $43m^2$.

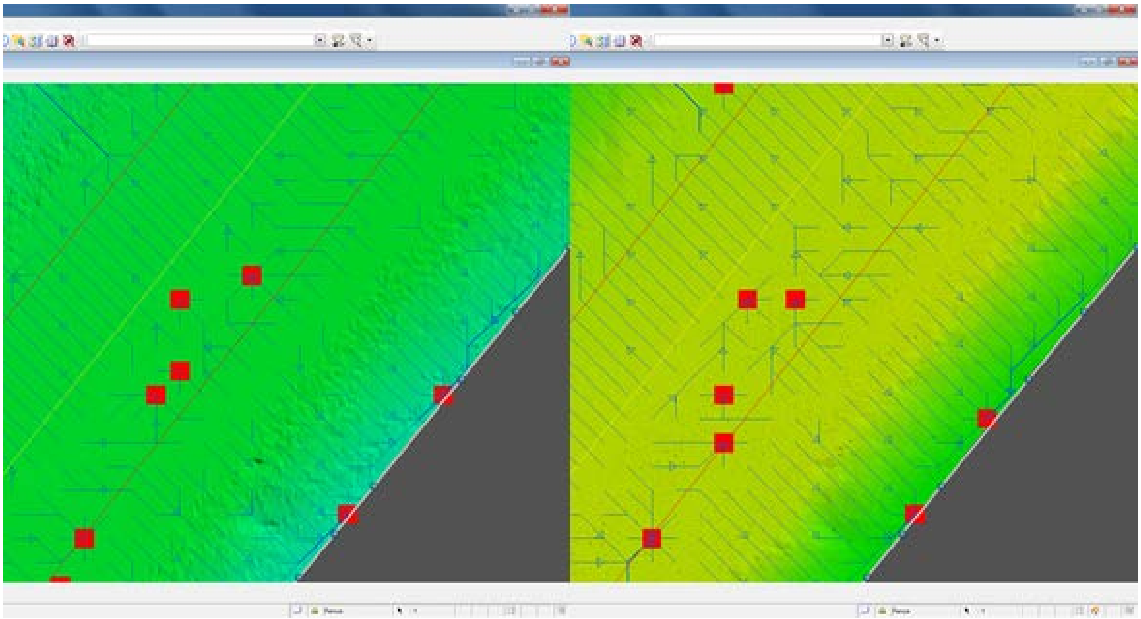

Figure 24: Road drainage comparison between ALS (left) and MLS data.

In the Rauma data set, the point density is much lower; road size is smaller and is not as active as the highway in the Jakomäki case. The speed limit is lower because this street is located close to the Rauma city center. The edges of the road are possible to recognize from the shadows of the ground surface visualization in Figure 25 and Figure 26. Centerline of the road is marked as a yellow line. In Figure 25, the point density is higher than in Figure 26. Between Figures 25 and 26, there is more variation than in Jakomäki case in Figure 24. The Rauma road environment is quite different compared with Jakomäki area.

The regions indicated by red squares are areas where water accumulates. On the right side of Figure 25, it can be seen from the locations of pour points that water drainage is not working properly. There are similarities in both lower density and higher density data but the runoff areas or locations of pour points vary. For the upper lane, the summed sizes of areas are 150m^2 for lower and 135m^2 for higher point density data. For the other lane, equivalent values are 124m^2 and 111m^2 respectively. Sizes of runoff areas for pour points are higher on the lower left corner of both images. In Figure 25, there are not water gathering points on the lower right corner and in Figure 26, runoff area sizes are small. On both images water flow, which is displayed with blue arrows, is rather similar. It is clearly seen that the highest point of the road is situated between the lanes since the water gathering points are next to pavement. The locations of the water gathering points are situated differently.

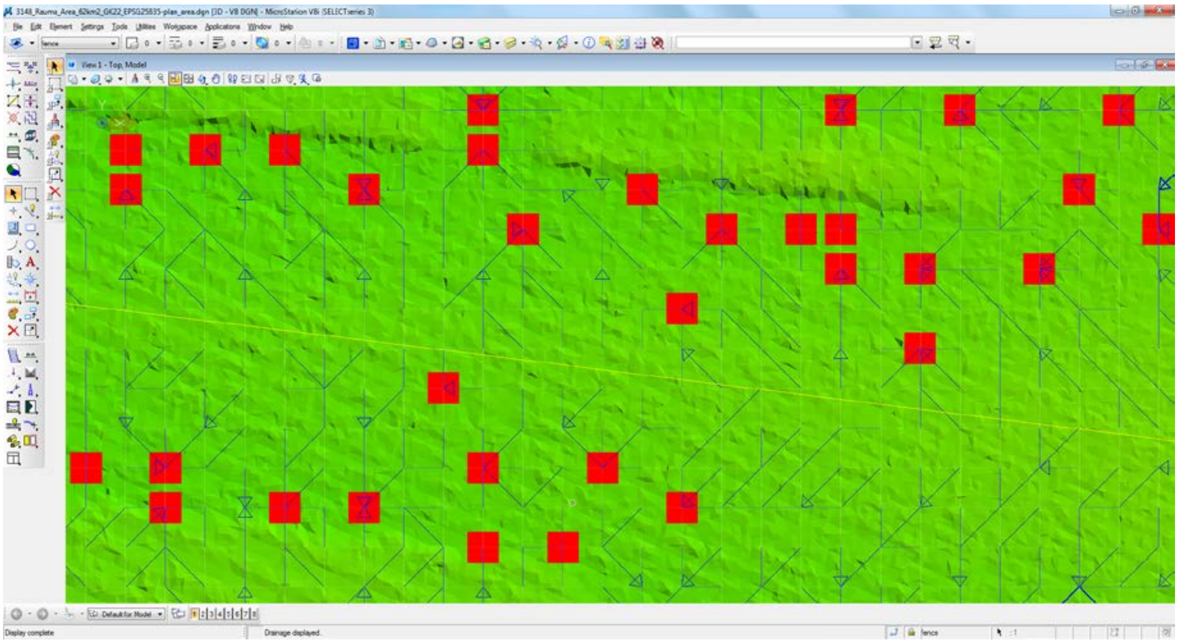

Figure 25: Road drainage displayed from higher point density data (Rauma).

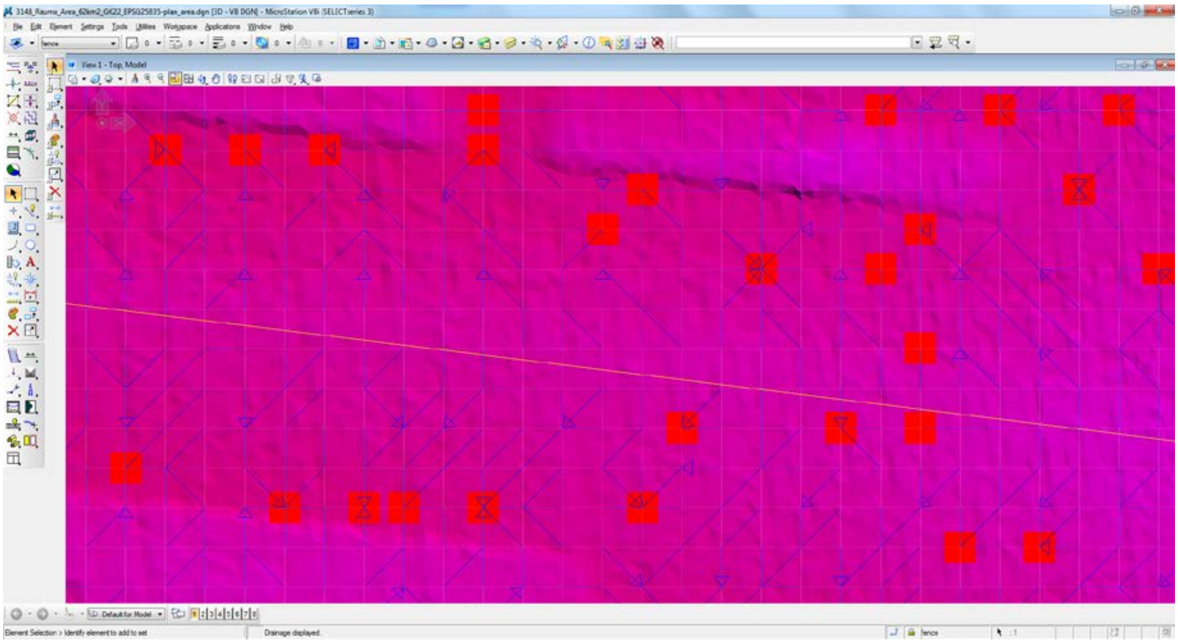

Figure 26: Road drainage displayed from lower point density data (Rauma).

Without any information about the locations of rainwater outlets, it is hard to say which of these pour points would actually flow to outlets and which would gather a puddle.

Many of the red squares are located right next to a pavement and rather close to each other. This means that longitudinal slopes are close to zero and the water is not flowing that much longitudinally. Since there are so many pour points displayed, even though there would be a rainwater outlet, it probably would not be enough to lead all the water out of the traffic lanes.

9.3 Individual tree detection in urban areas

Individual tree detection is still difficult especially in forests. Many algorithms and methods have been developed for that purpose. This thesis is focusing on obtaining planted trees in urban areas such as curbside trees. Detecting trees next to the street areas and the quality of detection is highly dependent on data processing and especially data classification in this method. A tree detection tool needs information about different classes, such as, ground and vegetation, to be able to compute the height above the ground. If the classification has failed and there are many points in wrong classes, the tree detection tool is not able to recognize trees, for example, when vegetation points are classified to building class. It is possible to find trees at three levels; fewer trees, normal level or more trees. When detection is complete in the urban areas for planted trees, it is best to choose the lowest level to find fewer trees. Typically, the problem in these kind of cases is to detect too many trees instead of one tree.

For actual tree detection, it is necessary to create tree models. Models need to be drawn in TerraScan settings using the cross section of trees. Tree shape has to be defined in two parts, first the centerline of the tree and then half of the tree crown. With this information, the software is able to create a full tree type model by mirroring the other half of the tree crown. (TerraScan user guide, 2012, p. 39.) Figure 27, is presenting an example of such a tree type model. Minimum and maximum heights can be defined depending on the tree species. The actual treetop is typically higher than the highest 3D-point. This is why it must be determined how much higher it is, for the software be able to draw the treetop close to its actual height. It is significant to define enough different tree types to get a successful result. It is good to have some idea about the dominant tree types in the area to create a comprehensive tree type list to get the best possible detection result. To get the best result in the area, it is needed to use general tree type models to detect the most occurring tree types. If the majority of the trees in the area are hardwood and the models have been made for softwood, the detection most probably will not be adequate. Larger trees are harder to recognize as one tree. Usually one large tree is recognized as two or more trees. This problem is hard to resolve out even if the tree type models are done successfully. If the size of the trees vary in the investigated area, the tree detection tool can consider one large tree as a few smaller ones. This tool detects more trees than what actually exists when trees are located close to each other and the leaves and branches are overlapping.

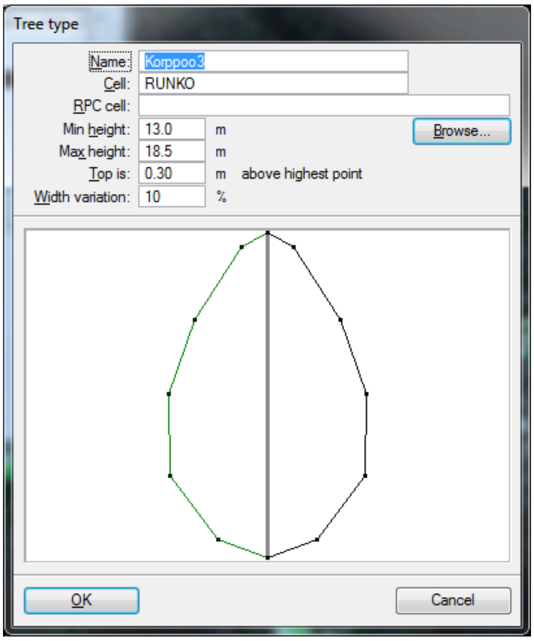

Figure 27: Typical tree type model created in TerraScan.

In the Korppoo area, the locations of 17 trees were surveyed to get reference data for automatic tree detection. The heights of the trees were determined automatically and manually from 3D point cloud data. Results between automatic and manual methods were compared. Even if the height of the tree is manually measured from the dataset, it might differ from real height because laser scanners are not always able to collect the top points of tree crown. In Figures 28-30, red lines are representing the surveyed location and yellow lines are the results of the automatic detection.

The heights of the trees were investigated and the automatic results were compared with manual measurements from red lines. Heights of the trees were determined from 3D point cloud data. Tree heights were measured within half meter accuracy. Most of the heights were the same regardless of the method used. The largest differences were on the trees in which the location of automatic and surveyed detection varied significantly. Maximum difference in the dataset was 6 meters in height but the variation in location for the same tree was over 3 meters. In such cases, it is obvious that results varies more. The second largest variation in height was 2 meters and the difference in location was also over two meters. If the location is in the wrong place, the height will vary too. Height is typically lower in automatic recognition than when measuring manually. The average difference between height detection methods was 0.6 meters. Figure 28, is an example of successful individual tree detection. Two trees on the image were surveyed and the automatic detection found the trees with good accuracy. The difference on the left side tree was only nine centimeters and on the right side tree it was 60 centimeters. Height difference between automatic and the manual method was within one meter.

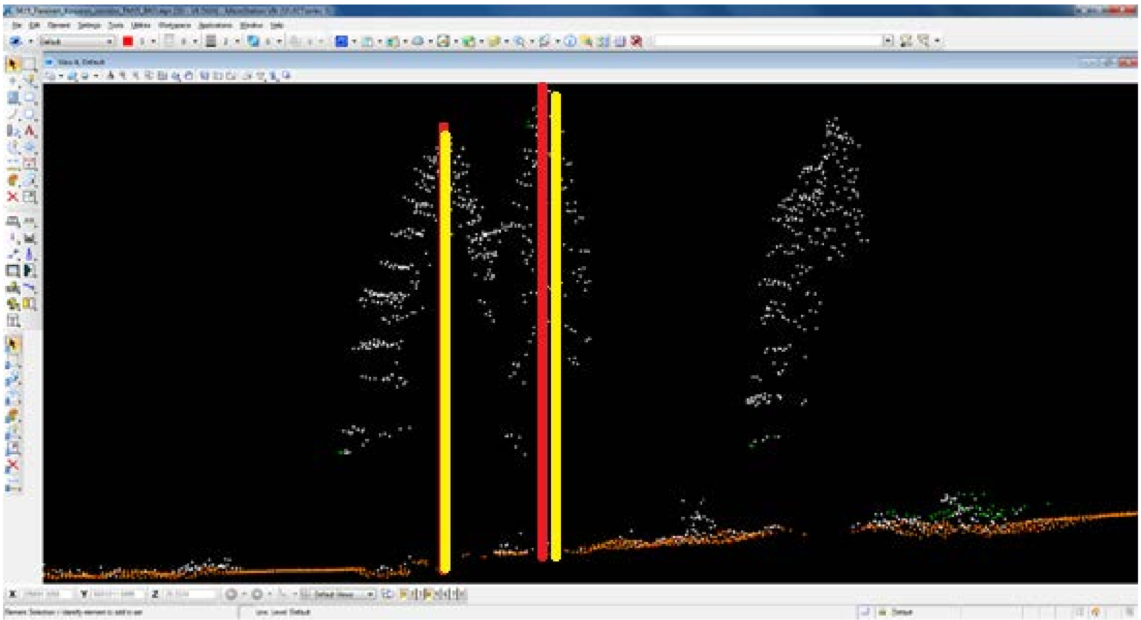

Figure 28: Difference between surveyed and automatic detection for the tree on the left side was 9 cm and on the right side 60cm.

The minimum difference between the surveyed and automatically found location was nine centimeters and the maximum difference was 3.1 meters. Two of the surveyed trees were not obtained when TerraScan's tool was used to detect the trees. One tree was found as two trees as it can be seen from Figure 29. The surveyed tree looks like it has two treetops. Automatic recognition has detected the tree trunks straight under those higher tops. These kinds of errors are hard to avoid since the models are simplified like in Figure 27. Even if a specific model with "two treetops" would be used for detecting the tree, in Figure 29, with TerraScan tree detection tool would still obtain trees under the "two treetops" because the shape of these kinds of "two treetops" trees will qualify with the other tree type models. Especially in this case: it looks like there are two trees really close to each other instead of one tree.

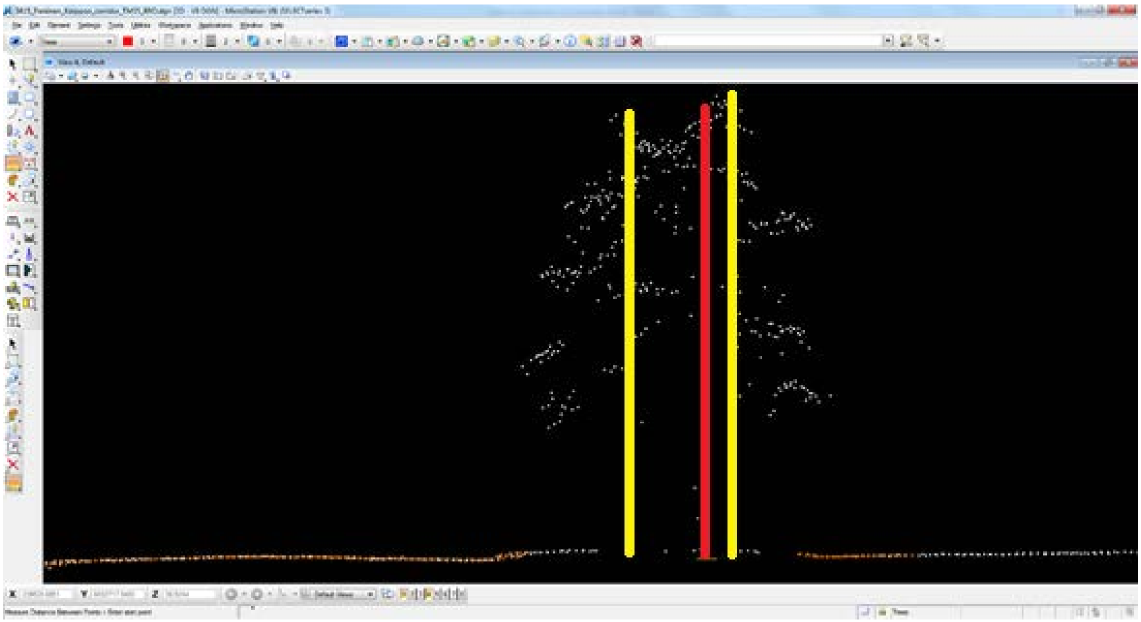

Figure 29: Automatic detection recognized one tree as two trees. The differences between surveyed and automatic detection were 240cm and 90cm.

In some cases, it is difficult to detect the tree due to lower vegetation like in Figure 30. Lower vegetation complicates the identification because then the actual tree's cross section does not match to any defined tree type models. Automatic recognition has detected the tree on the left side of the actual tree. On the right side, a shrub layer is higher and the clear shape of the tree is vanishing. Difference in height between automatic and manual results was about 6 meters, which was the worst result for automatic height determination. The average accuracy in location was about 1.2 meters, which can be considered as a good result. Average height for manually measured trees was 16 meters and if the locations of trees are automatically obtained within one meter accuracy, trees can still be identified.

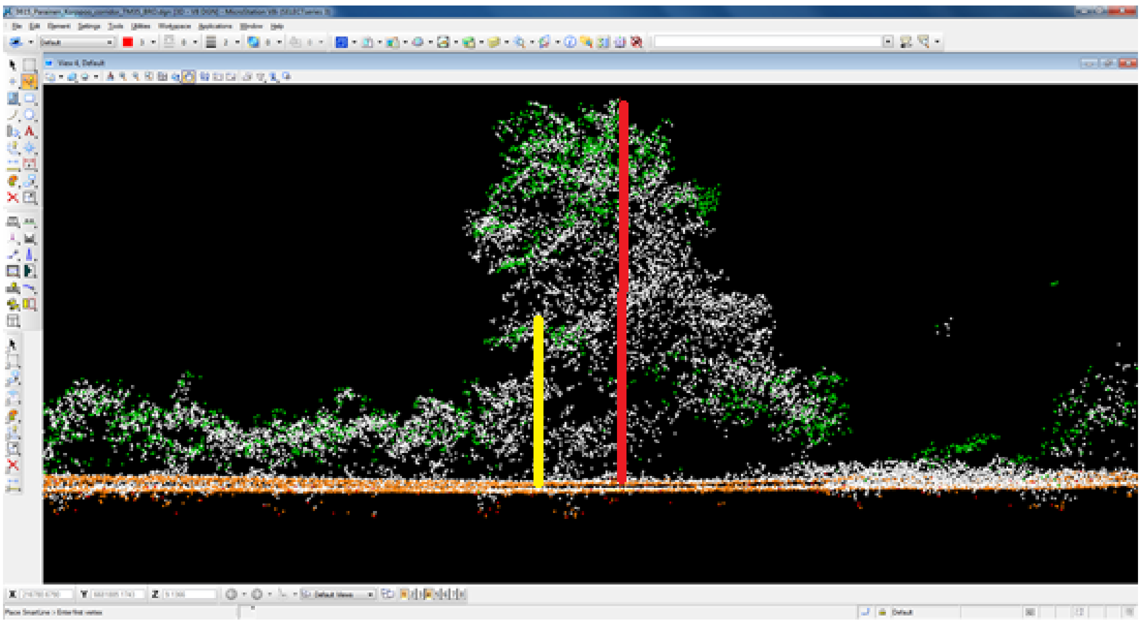

Figure 30: Influence of lower vegetation to automatic tree detection. Difference between surveyed and automatically detected location is 310cm.

10 Summary and conclusions

Methods that have been used earlier and are still used nowadays for the road damage inventory are time consuming and the process is not efficient. Especially when the inventory is done visually, the results obtained from same section of road may differ. It also needs a lot of manual work to go through the whole process. The laser road surface tester and 3D ground penetrating radar are collecting significantly less points than laser scanning methods. This makes rut detecting more challenging. For detecting road damages, it would be ideal to have both the mobile laser scanned data and BlomSTREET panoramic images. Mobile laser scanners provide high point density data and BlomSTREET service provides georeferenced and high-resolution images. The results from lidar data can be exported to BlomSTREET for verifying the results. BlomSTREET is a good service for road damage control and management among other things. Elevation models are common products produced from helicopter-based lidar data. Helicopter-based data can be used to monitor condition of the road with certain qualifications. It is interesting to know what other purposes it can be utilized. It may increase the value of the data since it can be used in many applications. When laser scanning is coming more common and the equipment cheaper, and especially when automatic algorithms are developing, it will come more popular in different fields of studies.

In the investigated part of the highway, in Jakomäki, no significant road damages were detected. Some rutting could be detected but the road was still classified mainly as good and satisfactory classes. The comparison between helicopter-based and MLS data would have been more informative, if there had been clearer road damages to detect. Then it would be easier to see the differences and the similarities between the results. If the mobile laser scanning is performed only from one lane, the point density differs greatly between the traffic lanes. The best result is acquired when the MLS vehicle is driven every lane once, producing smooth point density in the investigated area. When point density is high, it is possible to obtain smaller road damages and changes in the road surface. TerraScan tools for detecting road parameters are mainly developed for MLS data. This means that some of the parameters calculated from helicopter-based point cloud data are not accurate and cannot be utilized. Especially in Rauma's lower point density data, there were many gaps in the results because point density was not high enough for calculating road section parameters. It can be seen that when there is insufficient density, TerraScan determines the rut depths accurately to lines but to wrong locations, too close to the break line. Left and right rut depths are the only road section parameters whose exact X-Y -locations can be determined visually in MicroStation. For other parameters, location is situated on certain line, not as a point.

Most methods, utilized in this thesis, require a lot of manual work and analysis of the results. In Hyvinkää case, for example, the main road damages from the road section were obtained with large differences between adjacent longitudinal the road -slope arrows. However, large differences were not always a sign of road damage. A raised pedestrian crossing was detected from the highest percentage differences between sequential slope arrows. When the deviation between two adjacent or sequential arrows is large, these locations should be checked from images if those are available. Checking is a manual process, which means that it is rather time-consuming process. For example, ruts are usually darker lines in the asphalt and can be identified from the images. Not all bumps can be obtained from the images but from lidar data, it is possible to detect when the point density is high enough. Lidar data is a good way to get accurate information about slopes and road drainage. These are possible to obtain even from lower point density data.

Terrasolid's software TerraScan and TerraModeler have tools for showing slopes and TerraModeler has specific tools for displaying drainage. If the point cloud is colored by slopes, it is possible to detect rutting. When the locations of right and left rut depths are drawn into MicroStation, colored point cloud can be utilized for comparing the results. If in the point cloud data, the colored ruts are in the same line as the ones computed with TerraScan, the results are similar, rut locations can be determined.

In the Rauma lower point density data, it is possible to receive reliable information only from drainage and slopes. The highest point (road crown) of the road is between the lanes and there was sidewalk on both sides of the road. With the help of slopes, it is possible to obtain, that water flow is lead off from the center of the road. Longitudinal slopes determines if the water is stuck next to pavement or if it is lead to rainwater outlet. It is important to know the locations of rainwater outlets to know the actual water gathering points. This can be done, for example, in BlomSTREET. Longitudinal slope arrows, can be utilized for detecting longitudinal slopes. These slopes can be computed only for centerline or for the whole area. Values depend much on the location where those have been calculated. Longitudinal slopes can be different on the left and right edges, which is important to take into account when deciding the location where the slope arrows are computed. Slopes give information of both longitudinal and cross-section damages. It is hard to detect the depth and type of the damage.

Trees were measured from several places and the automatic detection was made for only those small areas. Individual tree detection was applied separately for every area. If all surveyed trees in a certain area would have been measured and the tree detection tool used to detect trees in the same area, the percentage of correctly detected trees would probably have been worse. Successful detection needs high quality tree shape -models and knowledge about tree types in the investigated area. Because every tree's shape is unique, it is hard to fit all trees in these shape models. The location of a tree trunk might be hard to identify, if there are no points detected from it. In addition, the trunk is rarely located right under the treetop. Tree heights were from ten to twenty meters in Korppoo area. Trees can still be identified even though the trees detection in meter accuracy with automatic methods. This accuracy is enough for tree registers.

When tree locations are automatically detected to the wrong place, the automatic tree height detection also varies more from the actual height. If the tree location is obtained within a meter, the height is obtained as well in meter accuracy with these methods used in this thesis. The best results are from the areas where planted trees are clearly individual and branches are not overlapping. If the tree species are the same and the shape of the trees are alike it improves the results. This is why it is preferred to have information about the tree species in the investigated area. Lower and medium vegetation are making the detection more challenging because the shapes of the trees are not that clearly visible when there are for example shrubs. Tree shape –models are not taking these into account and in these kind of cases, successful tree detection is unlikely. Tree detection can be utilized in addition to tree register, in biomass modeling and visibility analysis. Biomass modeling in urban areas has not been that significant in Finland since 86% of the land area is covered with the forest. In some other countries biomass modeling in urban areas might be more relevant. Visibility analysis can be utilized to improve, for example, traffic safety. Traffic signs might be hidden or the visibility is not enough in the road crossing areas, because the trees are blocking the view. These are some examples that can increase the probability for accidents. Some of the tree species can be recognized by using BlomSTREET images.

BlomSTREET panoramic and georeferenced images are good to use as a reference data. Results can be imported from MicroStation to BlomSTREET and vice versa. This is a convenient way to locate road damages and compare the results. Displaying drainage in TerraModeler shows the largest problem areas. If the results are imported to BlomSTREET, it is necessary to zoom in close, to examine the results in BlomSTREET. With this combination, it is clearly seen where the water flow stops and gathers. When collecting the BlomSTREET data, the same images can be utilized for road applications and tree detection in urban areas since the cameras are mounted in boats or cars. With this data, together with ALS or MLS data, it can be widely used for monitoring the road environment. Controlling the condition of traffic signs and bus stops are few examples where this kind of data combination can be utilized.

While doing this thesis, some topics surfaced for further research. BlomSTREET can already be utilized, for example, automatic traffic sign and lamppost inventory. It would be interesting to know, if it could be used for the automatic individual tree detection. How good the detection results would be with pattern recognition methods and would the accuracy be enough, for example, to utilize in tree registers and visibility analysis. In addition, one interesting topic is, if it is possible to identify the tree species.

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Attachments

Attachment 1:

1. Jakomäki parameters

	ALS			MLS			ALS-MLS		
Right	Max	Min	Average	Max	Min	Average	Max	Min	Average
MaxDev (m)	0,033	-0,072	-0,0028	0,011	-0,019	-0,0098	0,046	-0,06	0,007
LeftRut (m)	0,072	0	0,0065	0,02	0,003	0,0105	0,064	-0,015	-0,004
RightRut (m)	0,032	0	0,006	0,02	0,002	0,0113	0,021	-0,014	-0,0053
MaxRut (m)	0,072	0,001	0,0088	0,021	0,006	0,013	0,059	-0,015	-0,0041
	ALS			**MLS**			**ALS-MLS**		
Left	Max	Min	Average	Max	Min	Average	Max	Min	Average
MaxDev (m)	0,077	-0,178	0,0003	0,019	-0,021	-0,0059	0,09	-0,163	0,0063
LeftRut (m)	0,033	0	0,0047	0,018	0,001	0,0075	0,025	-0,013	-0,0027
RightRut (m)	0,185	0	0,0061	0,027	0,003	0,01	0,173	-0,026	-0,0038
MaxRut (m)	0,185	0,001	0,0075	0,027	0,003	0,0104	0,169	-0,024	-0,003
Average distance	Right ALS	Right MLS	Left ALS	Left MLS					
between ruts (m)	1,12	1,62	1,26	1,63					
Difference between									
adjacent slope arrows	Right ALS	Right MLS	R ALS-MLS	Left ALS	Left MLS	L ALS-MLS	Along ALS	Along MLS	
Max (degrees)	*1,64	0,11	2,01	0,34	0,13	0,26	0,56	0,1	
Average (degrees)	0,05	0,02	0,08	0,031	0,02	0,043	0,03	0,01	
*Point density variation due to truck									

2. Rauma parameters

	High point density			Low point density			High-Low		
Right	Max	Min	Average	Max	Min	Average	Max	Min	Average
MaxDev (m)	0,089	-0,094	-0,0063	0,074	-0,093	-0,005	0,131	-0,132	-0,0016
LeftRut (m)	0,085	0,006	0,0403	0,08	0	0,0228	0,081	-0,048	0,0178
RightRut (m)	0,115	0,009	0,0432	0,087	0	0,0247	0,115	-0,065	0,0182
MaxRut (m)	0,115	0,025	0,0554	0,097	0,003	0,0407	0,088	-0,058	0,0149
	High point density			**Low point density**			**High-Low**		
Left	Max	Min	Average	Max	Min	Average	Max	Min	Average
MaxDev (m)	0,072	-0,083	-0,0136	0,069	-0,109	-0,0082	0,125	-0,113	-0,0055
LeftRut (m)	0,113	0,009	0,0404	0,083	0	0,0238	0,088	-0,056	0,0171
RightRut (m)	0,086	0	0,0418	0,117	0	0,0265	0,068	-0,084	0,0152
MaxRut (m)	0,113	0,023	0,0528	0,125	0,003	0,0399	0,079	-0,081	0,0129
Average distance	Right High	Right Low	Left High	Left Low					
between ruts (m)	1,14	0,43	1,17	0,47					
Difference between									
adjacent slope arrows	Right high	Right low	High-Low	Left high	Left low	High-Low	Along high	Along low	
Max (degrees)	1,37	2,34	2,02	1,32	1,58	1,52	**	**	
Average (degrees)	0,18	0,27	0,25	0,17	0,27	0,25	**	**	
** Were not able to calculate									

3. Hyvinkää parameters

Right	Max	Min	Average
MaxDev (m)	0,082	-0,042	0,003
LeftRut (m)	0,041	0	0,0175
RightRut (m)	0,04	0,001	0,0162
MaxRut (m)	0,056	0,01	0,0239
Left	**Max**	**Min**	**Average**
MaxDev (m)	0,047	-0,048	-0,0018
LeftRut (m)	0,044	0	0,0202
RightRut (m)	0,042	0,006	0,0202
MaxRut (m)	0,051	0,01	0,0264
Average distance	**Right**	**Left**	
between ruts (m)	0,15	0,14	
Difference between			
adjacent slope arrow	**Right**	**Left**	**Along**
Max (degrees)	0,71	1,21	7,47
Average (degrees)	0,17	0,21	0,86